Nat. Hazards Earth Syst. Sci. Discuss., 2, 7367–7381, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/7367/2014/
doi:10.5194/nhessd-2-7367-2014

Natural Hazards and Earth System Sciences
Open Access
Discussions

Pre-earthquake magnetic pulses

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Received: 22 September 2014 – Accepted: 19 November 2014 – Published: 9 December 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

A semiconductor model of rocks is shown to describe unipolar magnetic pulses, a phenomenon that has been observed prior to earthquakes. These pulses are generated deep in the Earth's crust, in and around the Hypocentral volume, days or even weeks before Earthquakes. They are observable at the surface because their extremely long wavelength allows them to pass through kilometers of rock. Interestingly, the source of these pulses may be triangulated to pinpoint locations where stresses are building deep within the crust. We couple a semiconductor drift-diffusion model to a magnetic field in order to describe the electromagnetic effects associated with electrical currents flowing within rocks. The resulting system of equations is solved numerically and it is seen that a volume of rock may act as a diode that produces transient currents when it switches bias. These unidirectional currents are expected to produce transient unipolar magnetic pulses similar in form, amplitude, and duration to those observed before earthquakes, and this suggests that the pulses could be the result of geophysical semiconductor processes.

1 Introduction

Rocks, especially igneous rocks, behave as semiconductors under certain conditions (Freund, 2002, 2010; Freund et al., 2006; King and Freund, 1984). Although the magnetic fields produced by small semiconductors are often negligible, semiconductors on geophysical scales may produce significant magnetic fields. This is of particular interest since these fields can be observed at the Earth's surface and they seem to indicate that rock is being stressed deep in the crust.

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Ultra-low[1] frequency (ULF) electromagnetic emissions have been observed prior to earthquakes (Bleier et al., 2009), possibly resulting from electric currents flowing deep in the crust (Bortnik et al., 2010). Increased levels of magnetic fluctuations have been repeatedly observed prior to earthquakes since at least 1964 (Moore, 1964), but these transient phenomena are not yet fully understood and their applicability as earthquake precursors remains controversial within the geophysical community. For example, one of the most frequently cited magnetic anomalies preceded the Loma Prieta earthquake (Fraser-Smith et al., 1990). Some authors dismiss this as normal geomagnetic activity enhanced by operator or amplifier malfunction (Campbell, 2009; Thomas et al., 2009a), while counterarguments (Fraser-Smith et al., 2011) point out that continuous calibration tests should preclude this as a possiblity, that the precursor lacks the diurnal behavior of typical geomagnetic activity, and that amplifier malfunction would not preferentially amplify low-frequency signals.

Observed pre-earthquake electromagnetic waves typically have frequencies between 0.01 and 20 Hz, possibly owing to the fact that only low-frequency components may traverse tens of kilometers through the rock column. The study of such magnetic anomalies is complicated by the fact that large, unexplained variations in the magnetic field are deliberately removed from USGS data products (Thomas et al., 2009b) under the presumption that they are manmade.

During the weeks leading up to the $M = 5.4$ Alum Rock earthquake of 30 October 2007, a magnetometer located about 2 km from the epicenter recorded unusual non-alternating magnetic pulses, reaching amplitudes up to 30 nT (Bortnik et al., 2010). The incidence of these pulses increased as the day of the earthquake approached. A pair of magnetometer stations in Peru recently recorded similar unipolar pulses prior to several medium-sized earthquakes, and triangulating the source of these pulses revealed the location of subsequent earthquake epicenters (Heraud et al., 2013).

[1] In this context, "ultra-low" refers to electromagnetic waves having frequencies from millihertz to a few Hertz, in contrast to the International Telecommunications Union (ITU) definition of ultra-low, which would correspond to waves having frequencies of 300 Hz–3 kHz.

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The unipolar magnetic pulses observed prior to earthquakes have a characteristic shape that can be seen in Fig. 2. The unipolar nature of the magnetic pulses is somewhat unusual and bears resemblance to pulses produced by lightning and other electrical breakdown phenomena. However, the duration of many pre-earthquake pulses exceeds several seconds, much longer than any lightning strike. Moreover, triangulation of such pulses near Lima, Peru revealed that strong pulses originated almost exclusively from locations within a few kilometers of future earthquake epicenters (Heraud et al., 2013).

To model the electromagnetic phenomena associated with volumes of rock, we solve a three-dimensional drift-diffusion model of a semiconductor and calculate the magnetic fields induced by its electric currents. The model is seen to describe transient low-frequency unipolar magnetic pulses.

2 Rocks as semiconductors

The conductivity of crustal rocks in fault zones has been measured by magnetotellurics (Unsworth et al., 1999) and found to be typically 0.1–1 Sm^{-1}. These rocks are thus expected to behave as semiconductors, having conductivity typically ranging from that of silicon to germanium. We will show that unipolar pulses can emerge simply from the electrical drift and random diffusion of charge carriers in a semiconducting volume of rock. There are several reasons why this is a plausible mechanism for the observed pulses. Large electrical currents are known to accompany earthquakes, occasionally so large that luminous effects known as earthquake lights (Thériault et al., 2014) become apparent. There is experimental evidence (Freund, 2002, 2010; Freund et al., 2006; King and Freund, 1984) indicating that, during stressing, electrons and holes are freed in igneous rocks and become available to populate states in the valence and conduction bands.

One proposed source of charge carriers in rock is the break-up of peroxy defects (Freund, 2002, 2010; Freund et al., 2006) as a result of the increase in tectonic

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stresses. The oxygen sublattice of a wide variety of silicate minerals can form peroxy defects that act as sources of electron/hole pairs (Freund, 2010), causing these minerals to exhibit semiconductivity. Once activated, highly mobile electronic charge carriers diffuse through the minerals.

Peroxy defects are point defects, typically introduced through the incorporation of H_2O into nominally anhydrous minerals that crystallize in H_2O-laden magmas or recrystallize in high-temperature H_2O-laden environments (Freund, 2010). The incorporation of H_2O into oxides and silicates leads to OH^- pairs that subsequently undergo redox conversion. The two H^+ of the OH^- pairs combine to form H_2, and the O^- ions bind to form a peroxy bond. The formation of these peroxy bonds has been extensively studied in laboratory experiments (Freund, 2010, 2002; Freund et al., 1991; Griscom, 2011) and treated by computational chemistry (Ricci et al., 2001).

When peroxy bonds are energized via stresses in the rock or by heat, they may produce electron-hole pairs. The peroxy bond breaks, forming a transient state with two unpaired electrons. This is followed by a fully dissociated state in which a hole is free to move through the crystal structure. A neighboring oxygen atom donates an electron and becomes a hole, as its valence shell becomes deficient by one electron. The donated electron becomes trapped near the broken peroxy bond (Griscom, 2011) in a new state whose energy level is slightly below the upper edge of the valence band. In terms of the valence state, the neighboring oxygen atom, which was previously in an O^{2-} state, becomes O^-. This oxygen anion in the 1- state is effectively a positive hole with an incomplete valence shell and could also be regarded as an unstable oxygen radical (Freund, 2002).

Holes are capable of propagating through the oxygen lattice, exchanging valence electrons by a phonon-assisted vacancy hopping mechanism (Shluger et al., 1992). This process effectively constitutes a diffusion of O^- holes through a lattice of O^{2-} atoms. The trapped electrons are immobile but participate through recombination and electrostatic interactions.

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3 Drift-diffusion semiconductor model

The drift-diffusion equations are the most frequently used model for semiconductor physics, and perform well on scales greater than about $5\,\mathrm{m}^{-7}$ (Vasileskaet al., 2008). They describe current in terms of charge carrier concentrations and an electrostatic field, and this determines the change in charge carrier concentrations via continuity of the current density. The drift-diffusion equations are:

$$\begin{aligned}
\partial_t \boldsymbol{n} &= -\boldsymbol{R}(\boldsymbol{n},\boldsymbol{p}) + \nabla\cdot(D_n\nabla\boldsymbol{n} - \mu_n\boldsymbol{n}\nabla V)\\
\partial_t \boldsymbol{p} &= -\boldsymbol{R}(\boldsymbol{n},\boldsymbol{p}) + \nabla\cdot(D_p\nabla\boldsymbol{p} + \mu_p\boldsymbol{p}\nabla \boldsymbol{V})\\
\Delta \boldsymbol{V} &= \frac{1}{\epsilon}(\boldsymbol{n}-\boldsymbol{p}-\boldsymbol{C}).
\end{aligned} \tag{1}$$

Here, $\boldsymbol{n}$, $\boldsymbol{p}$, $\boldsymbol{R}$, $\boldsymbol{V}$, and $\boldsymbol{C}$ are defined on a domain $\Omega\times(0,T)$, where Ω is a subset of a 3-dimensional space. The functions $\boldsymbol{n}$ and $\boldsymbol{p}$ are concentrations of electron and hole charges, respectively, and $\boldsymbol{C}$ is the charge of any dopant ions that are present. $\boldsymbol{R}(\boldsymbol{n},\boldsymbol{p})$ is the recombination/generation rate of electrons and holes. The third equation is Poisson's law of electrostatics whose solution describes the electric potential $\boldsymbol{V}$. ϵ is the electric permittivity. The constants μ_n and μ_p are the mobilities of electrons and holes, respectively, (not to be confused with the magnetic permeability μ or μ_0) and D_n and D_p are the corresponding diffusion coefficients. In the particular instance of the model under consideration, μ_n and D_n are approximately zero due to electrons becoming trapped in the valence band.

4 Coupling electromagnetism to drift-diffusion

Maxwell's equations describe propagation at the speed of light, which is much faster than the charge carriers diffusing in a typical semiconductor. Rather than modeling propagation on two very different time scales, we make use of a quasi-static (magneto-static) approximation (Jackson, 1999), assuming that currents do not alternate rapidly

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or approach the speed of light. Specifically, the Maxwell displacement current appearing in Ampere's law is assumed to be negligible: $c^{-2}\partial_t \boldsymbol{E} \approx 0$. This assumption is implicit in the drift-diffusion model due to its use of Poisson's equation for the static electrical potential.

The electric current density $\boldsymbol{J}(\boldsymbol{x}')$ acts as the source of a magnetic field. It may be expressed as the sum of a drift term, involving the electric field, and a diffusive term, involving the concentration gradient. The rate of change of the concentration then becomes a continuity equation that is a function of current density. Explicitly separating the current and continuity equations facilitates coupling to the magnetic field. In this form, the current densities are:

$$\begin{aligned} \boldsymbol{J}_n &= D_n \nabla \boldsymbol{n} + \mu_n \boldsymbol{n} \nabla \boldsymbol{V} \\ \boldsymbol{J}_p &= -D_p \nabla \boldsymbol{p} + \mu_p \boldsymbol{p} \nabla \boldsymbol{V}. \end{aligned} \tag{2}$$

The continuity equations that describe the change in electron and hole concentrations are, then:

$$\begin{aligned} \partial_t \boldsymbol{n} &= -\boldsymbol{R}(\boldsymbol{n},\boldsymbol{p}) + \nabla \cdot \boldsymbol{J}_n \\ \partial_t \boldsymbol{p} &= -\boldsymbol{R}(\boldsymbol{n},\boldsymbol{p}) + \nabla \cdot (-\boldsymbol{J}_p). \end{aligned} \tag{3}$$

The current densities $\boldsymbol{J}_n$ and $\boldsymbol{J}_p$ are summed to obtain the total current density $\boldsymbol{J}$ that acts as a source for the magnetic field. In a magnetostatic approximation, the solution to the magnetic field on a domain may be efficiently computed by solving a set of Poisson equations for the magnetic vector potential. In this case, however, we calculate the field at an arbitrary point in space, which could be outside the domain. We apply the Biot–Savart law to obtain the magnetic field at the point $\boldsymbol{x}$:

$$\boldsymbol{B}(\boldsymbol{x},t) = \frac{\mu}{4\pi} \int (\boldsymbol{J}_p(\boldsymbol{x}',t) + \boldsymbol{J}_n(\boldsymbol{x}',t)) \times \frac{\boldsymbol{x}-\boldsymbol{x}'}{|\boldsymbol{x}-\boldsymbol{x}|'^3} \mathrm{d}^3\boldsymbol{x}'. \tag{4}$$

Here, $|\boldsymbol{x}-\boldsymbol{x}'|$ is the magnitude of the vector from $\boldsymbol{x}$ to $\boldsymbol{x}'$ and μ is the magnetic permeability. The velocities of the holes are not sufficiently large for the Lorentz force to

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be significantly influenced by magnetic fields so we do not conisder the effect of the magnetic field on the charge carriers.

5 Numerical solution

The drift-diffusion equations are solved by expressing the partial differential equations as a system of ordinary differential equations for the time derivatives $\partial_t \boldsymbol{n}$ and $\partial_t \boldsymbol{p}$. A finite-difference approximation to this system is then integrated using a fourth-order Runge–Kutta scheme (RK4). Poisson's equation is solved separately at each timestep using successive over-relaxation (Golub and Van Loan, 1996) (SOR) with an adaptive relaxation parameter and open boundary conditions. For the other PDEs, the Dirichlet boundary conditions $\boldsymbol{n} = 0$ and $\boldsymbol{p} = 0$ are applied to the boundary of a grid of uniformly spaced points representing the x, y, and z coordinates over which functions are evaluated. All spatial partial derivatives (∂_x, ∂_y, ∂_z, ∇) of the current and continuity equations are approximated using a fourth-order central difference approximation.

At each timestep, the electric potential is determined by solving Poisson's equation, starting the SOR iteration with the electric potential from the previous timestep. Using the electric potential and the charge carrier concentrations, the components of the current vector fields $\boldsymbol{J}_n$ and $\boldsymbol{J}_p$ are evaluated. From $\boldsymbol{J}_n$ and $\boldsymbol{J}_p$, the continuity equations are integrated, yielding the concentrations of the charge carriers at the next timestep.

The magnetic field $\boldsymbol{B}$ is evaluated by applying a discretized Biot–Savart law to the currents. $\boldsymbol{B}$ is calculated at each timestep but since the result does not affect the dynamics, it may be evaluated at a single point.

6 Results

Since holes are mobile and electrons are immobile, diffusion separates the two species, creating an electric current that acts as an electromagnet. The boundary of a region of activated charge behaves, essentially, like the p-n junction of a diode. Since only

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holes may flow out of this volume, the initial current diffusing across the boundary is unidirectional, corresponding to forward bias in the diode. However, after a delay period during which recombination reduces the diffusive current, the diode could switch to reverse bias, whereby the *p*-*n* junction capacitance generates a reverse recovery current. In the case of a recovery current, holes flow back into the source volume, producing a magnetic pulse that is opposite in polarity to the initial magnetic field.

We use the semiconductor model to calculate an example of a unipolar magnetic pulse. The electric permittivity and magnetic permeability are estimated based on the static properties of MgO (Batllo et al., 1991) ($\epsilon \approx 16.75\epsilon_0$ and $\mu \approx \mu_0$) and a temperature of $T = 673.15\,\mathrm{K}$. Since electrons are trapped and immobile in broken peroxy bonds, μ_n and D_n are set to 0. The mobility and diffusion constant of holes were estimated based on experimental data from an experiment in which a rapid pressure impulse to the center of a gabbro tile injected holes that diffused and drifted away from their source, akin to a Haynes–Shockley experiment. The parameters used are $\mu_p = 0.063\,\mathrm{m}^2(\mathrm{Vs})^{-1}$ and $D_p = 8.5 \times 10^{-4}\,\mathrm{m}^2\,\mathrm{s}^{-1}$, roughly comparable to their values in pure undoped Silicon.

Charge generation is not explicitly considered in this calculation, and a pre-existing excess concentration of $10^{-5}\,\mathrm{C\,m^{-3}}$ of both electrons and holes is an initial condition. These dissociated charges are initially present only at grid points inside a piriform teardrop surface of the form $(z/4000)^4 - (z/4000)^3 + (x/2000)^2 + (y/1000)^2 = 0$. Their recombination rate is proportional to the product of electron and hole concentrations, $\boldsymbol{R} = 10^{22}\boldsymbol{np}$. The attenuation of the magnetic field as it passes through the Earth is not considered, nor are effects associated with the surface of the Earth.

Calculated and observed magnetic pulses are illustrated in Figs. 1 and 2. Fig. 1 shows the value of the x component of the magnetic field as a function of time, measured 10 km directly above the center of the simulated volume. The amplitude, frequency, and shape of the pulse are similar to pulses that have been observed before earthquakes. For comparison, Fig. 2 shows several magnetic pulses observed prior to an earthquake near Lima, Peru. These pulses were measured over a period of sev-

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eral days by a pair of magnetometers approximately 25 km away, and the locations of their sources were triangulated. The sources were clustered within a few kilometers of the epicenter of an earthquake that occurred two weeks after the onset of the pulses (Heraud et al., 2013). This analysis has been performed prior to several moderate earthquakes near Lima, with similar results.

7 Conclusions

When a volume of rock is stressed, excess holes and electrons are injected. The mobile holes begin to diffuse out of the source volume, while electrons are trapped within the source volume and undergo recombination with the holes that have not diffused out. The flux of holes leaving the source effectively creates a *p*-*n* diode: the source volume becomes an *n* type semiconductor and the surrounding rock becomes *p* type. A depletion region forms between the two layers of the *p*-*n* junction and the *p*-*n* double layer screens electric fields outside its immediate vicinity.

After charge injection, a diffusive current of holes flows as a result of the concentration gradient across the source boundary. This corresponds to a forward bias state of the diode, dominated by diffusion capacitance rather than junction capacitance. This current creates a transient magnetic field. As the hole concentration gradient decreases, the diffusive current and the magnetic field decay. After holes have diffused outward, creating *p* type and *n* type regions, a junction capacitance results from layers of positive and negative charge separated by a depletion region at the junction.

After a delay period, the diode may switch to a reverse bias state. In this case, electron-hole recombination consumes the holes remaining within the source volume, leaving mostly electrons inside. The junction capacitance causes a transient reverse recovery current. If the potential drop across the depletion region is sufficiently strong, reverse-bias electrical breakdown may occur as Coulomb attraction pulls holes back into the source volume.

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A distinctive form and the ability to pass through the earth at ultra-low frequencies make magnetic pulses a compelling tool for the observation of pre-seismic shifts in the stress level of rocks that are otherwise inaccessible due to depth. By triangulating the source of these magnetic pulses, the increased buildup of stress around future earthquake epicenters may be identified weeks in advance of seismicity.

In addition to unipolar pulses, other types of electromagnetic precursors might be predicted from the semiconductor model. Oscillatory ULF fields, for example, have been observed immediately preceding earthquake activity (Bleier et al., 2009).

The "positive hole" semiconductor theory modeled here seeks to unify a wide range of electromagnetic phenomena associated with seismic activity. The direct coupling of semiconductor drift-diffusion currents and electromagnetism produces a model consistent with observations of pre-seismic magnetic pulses. This suggests that pre-earthquake ULF activity may be the result of geophysical semiconductor processes.

Acknowledgements. The authors would like to thank Tom Bleier and Clark Dunson of QuakeFinder for many informative discussions. The authors would also like to thank Jiro Funamoto and Kim Johnson for their comments on the manuscript. This research was funded in part by NASA Earth Surface and Interior Grant NNX12AL71G (John LaBrecque).

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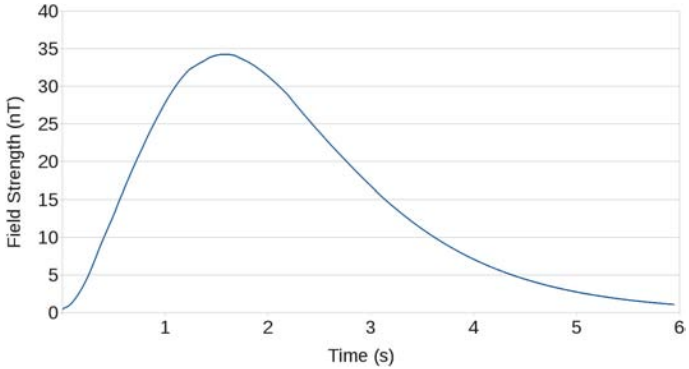

Figure 1. A calculated transient magnetic pulse, 10 km from the current source.

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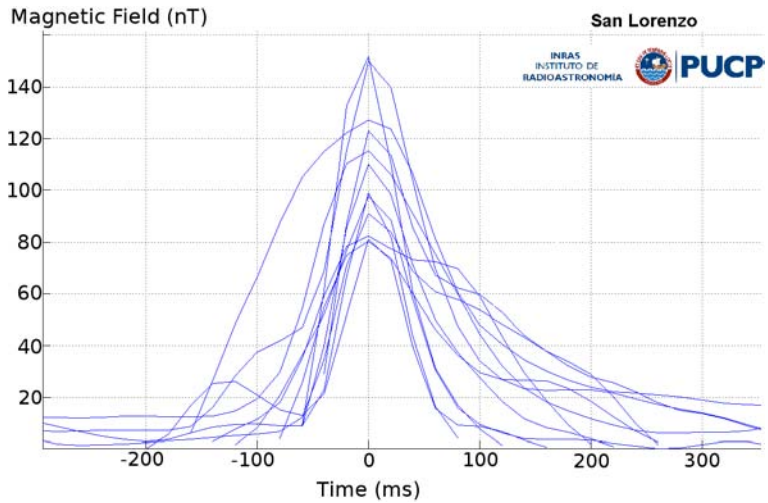

Figure 2. Magnetic pulses observed prior to an earthquake in Lima, Peru, approximately 25 km from the epicenter.

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Nat. Hazards Earth Syst. Sci. Discuss., 2, C2966–C2967, 2015
www.nat-hazards-earth-syst-sci-discuss.net/2/C2966/2015/

Natural Hazards and Earth System Sciences
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Discussions

Interactive comment on "Pre-earthquake magnetic pulses" *by* J. Scoville et al.

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Received and published: 6 January 2015

Dear Authors, I suggest you considering the following recent paper:

Dahlgren, et al. (2014), Comparison of the StressâĂŘStimulated Current of Dry and FluidâĂŘSaturated Gabbro Samples, Bull. Seismol. Soc. Am., 104(6), 2662–2672, doi: 10.1785/0120140144.

Dahlgren and his colleagues investigated charge generation as function of stress in gabbro both for dry samples and samples saturated with fluid. Similarly to previous experiments, stress-related electric currents were observed in dry samples. On the contrary, no electric current was generated in fluid-saturated samples during several cycles of stress loading. Since the Earth's crust is fluid saturated, Dahlgren, et al. (2014) conclude that significant electric currents are not expected to be generated the

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days before earthquakes during the slow stress accumulation in the region of earthquake nucleation. As a consequence, electric and magnetic signals are expected not to be observed on the Earth's surface.

In my opinion you should include in your manuscript a section in which the results of Dahlgren, et al. (2014) are discussed. Particular attention should be paid on the generation of magnetic pulses in the presence of fluids, as well as on how fluids influence magnetic pulses when they cross the Earth's crust. If the influence of crustal fluids is not discussed, your semiconductor model of rocks hypothesizes a merely dry (but not real) Earth's crust. This, however, must be pointed out in your manuscript.

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Interactive comment on "Pre-earthquake magnetic pulses" *by* J. Scoville et al.

J. Scoville et al.

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Received and published: 13 January 2015

Dear Dr. Masci,

Thank you for your comment. First, note that the data presented in the paper by Dahlgren, et al.[1] does not actually support its conclusion that "no electric current was generated in fluid-saturated samples during several cycles of stress loading." In fact, the "stress-stimulated currents" in fluid-saturated samples were much larger than those reported for dry samples. Figures 4b and 5b, attached, clearly show changes in electrical currents over the course of stress-loading cycles. It is unclear how or why the authors of this paper arrived at a conclusion that directly contradicts their experimental results, or how such an obvious contradiction could have been overlooked during the review process.

Moreover, the data presented by Dahlgren, et al. are incorrectly plotted as “currents” whereas the graph captions state they are “stress-stimulated currents” or “SSC”. This quantity, not the same as a physical electrical current, was apparently contrived for the purposes of this paper. Also note that its repeated reference to Freund (2002) is incorrect - the experimental setup does not appear there.

Dahlgren, et al. define “SSC” not as a current, but as a difference of currents. In the SSC, “baseline” levels of currents were subtracted from the data, so, in reality, the values plotted are not absolute currents, but rather offsets from a baseline value. Without information about the baseline currents, the SSC is meaningless. Ostensibly, this definition was introduced to take into account the effect of electrochemical (galvanic) potentials. However, it is more likely that these potentials actually result from the large pre-loading force that was applied to the samples before the baseline level was recorded. Referring to (and drawing conclusions from) the SSC values as if they were currents is not only misleading – it is not physically valid. The situation is somewhat reminiscent of a merchant zeroing the value of a scale while leaning on it.

There are many reasons that the experiments described by Dahlgren, et al. are not analogous to conditions deep in the crust. Liquid water can’t exist deep in the crust where temperatures exceed 400C. At these temperatures and pressures, water exists not as a liquid but as a supercritical fluid with very different physical and chemical properties. Also, the measurements involving fluid-saturated samples were actually of a circuit containing both a rock and a resistor, the latter having been introduced due to difficulties with an ammeter.

Furthermore, the presence of free water deep in the crust isn’t a fully established fact. It is one of several hypotheses that have been proposed to explain anomalous regions of high conductivity for which there is no generally accepted explanation. Alternative explanations include partial melting, intergranular carbon films, and – notably - peroxy defects[2]. Silicates that incorporate water into their structures form peroxy defects by a redox mechanism. In this way, our paper already describes one mechanism by which

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deep crustal water could lead to the generation of charge carriers and magnetic pulses.

In terms of more shallow liquid water between the source of a pulse and its observer, attenuation of magnetic fields through a conductive crust are considered in the study by Bortnik et al. referenced in our manuscript. In an attempt to keep the number of free parameters in our model to a minimum, we have not considered attenuation, reflection/refraction, surface geometry, etc. related to the propagation of electromagnetic pulses through the crust and the air/ground interface. A future study may consider these factors.

All this being said, the simplest response to your query, perhaps, is that at depths of more than a few kilometers the pore spaces of rocks are closed by the overload pressure. Without a connected pore space, no contiguous voids exist within the rocks for water or other fluids to fill.

Best regards,

John Scoville

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1. Dahlgren, P. R., M. J. S. Johnston, V. C. Vanderbilt, and R. N. Nakaba (2014), Comparison of the stress-stimulated current of dry and fluid saturated gabbro samples, *Bulletin of the Seismological Society of America*, 104, 2662-2672.

2. Freund, F. (2003), On the electrical conductivity structure of the stable continental crust, *Journal of Geodynamics*, 35, 353-388.

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 2, 7367, 2014.

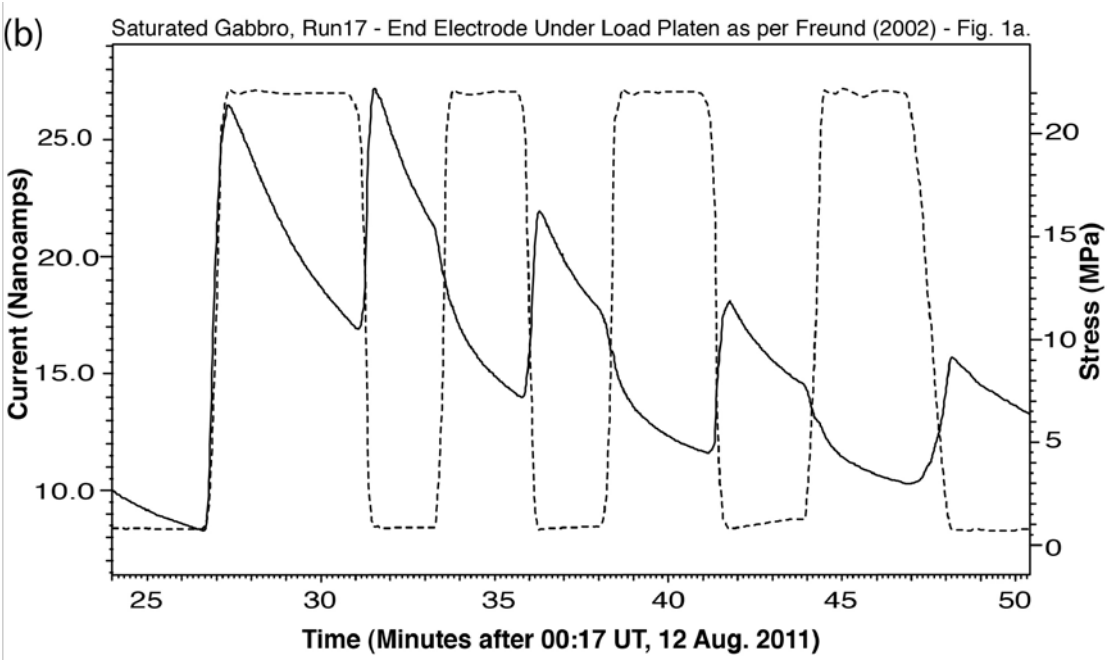

Fig. 1. Fig 4b, Dahlgren, et al. (2014)

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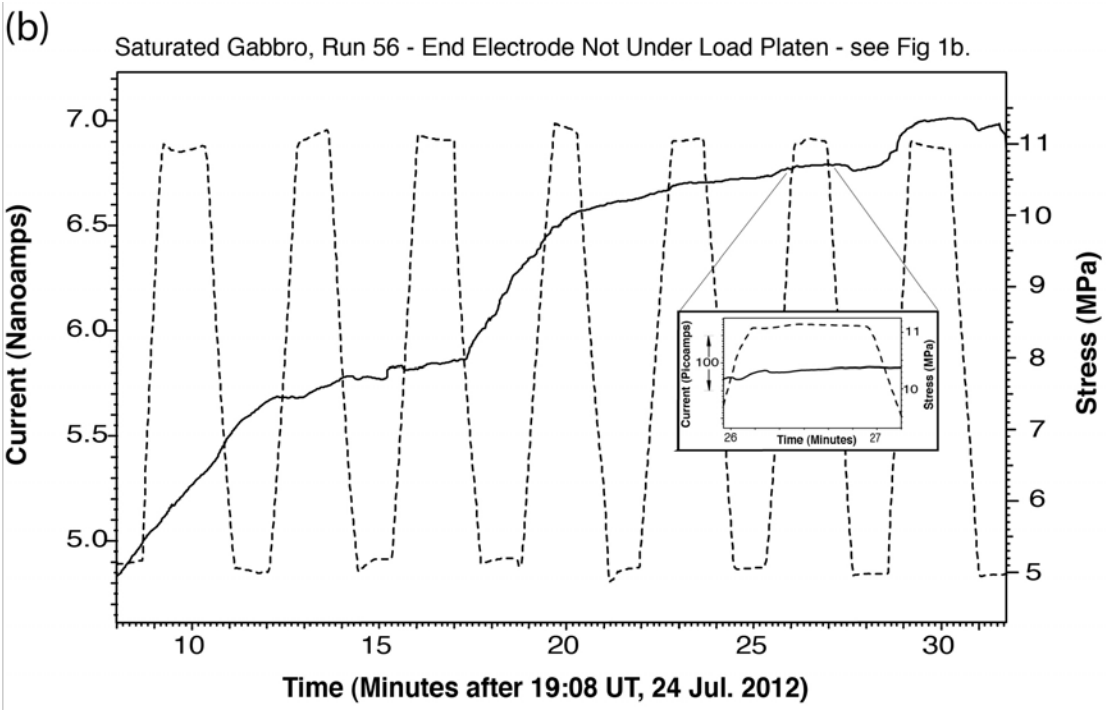

Fig. 2. Fig 5b, Dahlgren, et al. (2014)

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Nat. Hazards Earth Syst. Sci. Discuss., 2, C3020–C3022, 2015
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Discussions

Interactive comment on "Pre-earthquake magnetic pulses" *by* J. Scoville et al.

J. Scoville et al.

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Received and published: 13 January 2015

Communicated on behalf of F. Freund.

Dear Dr. Masci,

Dahlgren et al.* [DJVN] recently reported on rock stressing experiments which they had conducted at the NASA Ames Research Center as part of a collaboration that I had initiated – upon NASA's request – to resolve a longstanding disagreement between Malcolm Johnston and myself regarding the nature of the charge carriers that become activated when rocks are subjected to deviatoric stress. I was present at the start of the project, when Dr. Johnston insisted on preloading the rock samples, arguing that firm clamping was "common procedure in rock mechanics". I pointed out that preloading

is the worst thing to do, if the goal is to measure stress-activated electric currents in rocks. Unfortunately, for personal reasons, I was unable for some time to participate in the experimental work. During this time DJVN went ahead with their preloading procedure.

Why is preloading bad? Peroxy defects tend to be located along, even straddle grain boundaries. As soon as stresses are applied, grains will shift relative to each other, causing peroxy bonds to break and release highly mobile positive holes. These charges flow out of the stressed rock volume forming positive outflow currents. At the same time, the positive holes also recombine with half-lives ranging from milliseconds to hours, even days. As a result, the stress-activated outflow currents are inherently unstable, especially at the beginning of loading, when these currents vary non-linearly as a function of time and as a function of the rate at which stresses are applied.

The proper way to measure stress-activated electric currents is to start at 0 MPa, to make sure that the baseline currents are stable near 0 pA, and to end at 0 MPa. By clamping their rock samples, DJVN created conditions where the baseline currents varied wildly between –1000 pA and +450 pA for dry rock samples and tens of nA for water-saturated rocks. DJVN never made any attempt to validate their preloading procedure or to determine whether the stress-activated charge carriers are electrons or holes. Nonetheless they call currents that decrease "negative" currents. This is unphysical to say the least. A positive current that decreases is not a negative current.

DJVN's statement that the "negative sign . . . is inconsistent with the physical model of positive hole generation" can therefore be assumed to be based on a fundamental misconception of electric charge. Likewise, DJVN's statement that the alleged negative currents "raise questions about the applicability of the semiconductor p-hole theory proposed by Freund (2002) to explain the earlier results" is totally unfounded.

By the time I was able to rejoin, DJVN had completed their runs. NASA provided additional funds to finish the project and to repeat the experiments without preloading.

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However, DJVN never returned to complete the collaborative work. Instead they started to disseminate the results they had obtained – against my outspoken advice – with their preloading procedure and without any controls that would have uncovered the shortcomings of their approach. DJVN have taken this work, initiated as a collaboration, into a very one-sided, biased direction. They have not proven in any way what they allege to have shown. Referencing their paper would do science a disservice.

Sincerely,

Friedemann Freund

References:

* Dahlgren, P. R., M. J. S. Johnston, V. C. Vanderbilt, and R. N. Nakaba (2014), Comparison of the stress-stimulated current of dry and fluid saturated gabbro samples, *Bulletin of the Seismological Society of America*, 104, 2662-2672.

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 2, 7367, 2014.

Nat. Hazards Earth Syst. Sci. Discuss., 2, C1–C4, 2015
www.nat-hazards-earth-syst-sci-discuss.net/2/C1/2015/

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Interactive comment on "Pre-earthquake magnetic pulses" *by* J. Scoville et al.

J. Scoville et al.

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Received and published: 21 January 2015

Communicated on behalf of J. Heraud.
REFERENCE: J. Scoville, J. Heraud, F. Freund, Pre-earthquake magnetic pulses, NHESSD 2, C3029-C3030, 2015, Interactive Comment.

Dear Dr. Masci,

I would like to add a few comments to those already sent to you by my colleagues and co-authors.

I agree with your remarks in the Interactive Comment referenced above when you say "that the experiment of Dahlgren et al. (2014) does not fully match the physic-chemical condition of the Earth's crust, but also a merely dry crust does not *match reality*".

I think the last words are vital to the contribution of our paper. Let me bring to this discussion, another look at the context in which our paper came up. As we all know, any theory has to describe the phenomenon, make predictions, but essentially it should conform to, or as you put it "match", reality. In the research work I have been doing in Peru for the last seven years, I have encountered several good examples of the generation, propagation and detection of electromagnetic phenomena, with extreme care not to fall into false expectations, which conform to the theory of the generation of positive-holes in rocks pioneered by Dr. Freund. I met him as a consequence of one of my publications having to do with co-seismic light emission in the area of Lima, Peru highly time-correlated with the ground acceleration produced by the S-wave during the 2007 Ml 8.2 earthquake and I hypothesized that the electric charges that produced the light emissions were released locally, with the epicenter located about 160 km away. We coincided in appreciating the reality matching observations and in the conclusions connected with his research.

Besides studying light emissions, time was dedicated to develop a technique to reliably compute the azimuth for the arrival of the EM ULF pulses we observed after an earthquake in southern Peru, the second validation for similar phenomena observed by Quakefinder during the Alum Rock earthquake in California. The pulses, from about 0.01 to 1 Hz, had been conjectured, were produced in the Earth's crust and detected by our very sensitive 3-axis magnetometer network in Peru, consisting of 10 sites. A technique was thence developed to jointly process information from two of them, strategically deployed in the northern part of the bay of Lima, to triangulate the origin of the EM pulses and determine the geographic position of the stress area and try to predict the future epicenter. This was done successfully and the distance from our "predicted" future epicenters to the actual epicenter of the earthquake, has ranged from 0 to about 12 km in about a dozen observations. In about a year and a half, we have about a dozen hits in two areas of the country, about 1000 km from each other with no false negatives and in the few false positives we have, an earthquake has occurred, on the predicted day but in a nearby area in the south which looks seismically connected with

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the northern area. This alerts us that the possible two hundred km rupture between these areas, would mean a very high magnitude earthquake. Part of the above has been covered in the presentation cited in our paper, at AGU.

Although what I described is not the precise theme of this paper under discussion, it provides the experimental perspective for the model therein, since the pulses we are using, “to match reality”, come from the precise magnetometer sites described above. It constitutes a reality then, that EM ULF pulses are being produced about 10 - 50 km from the coast, at depths of 25 to 60 km, prior to an earthquake. It is a reality that they can propagate through rock and sea water, for at least 75 km and perhaps 95 km, from observations in other magnetometer sites we operate in Peru. It is a reality that the computational results described in our paper under discussion, match outstandingly well the observed mono-polar pulses that nature produces, particularly in those cases where we can observe that an earthquake has occurred just a few kilometers away from the source detected, ahead of time, of ULF pulses with our magnetometers in Peru. EM pulses do occur, they are currently being used by my group in Peru to predict earthquakes and our paper, I think, models quite well their generation process.

The propagation of ULF signals in the lithosphere beneath the ocean bed, as well as on the sea water has been studied for some years now for practical purposes, especially for submarine communications and underwater detection. Even though useful bandwidths are very small, in some cases not more than a few Hz, it is enough to convey simple but potentially vital information on geophysical phenomena that can be used advantageously. Chave, Flosadottir and Cox[1] consider a model for the electrical conductivity beneath the deep seafloor using, precisely, geophysical evidence. Their model consists of relatively conductive sediment and crustal layers of 6.5 km on a sub-crustal channel of 30 km thickness. They found that significant enhancement of the field amplitude can occur at long ranges (> 100km) and low frequencies (<1 Hz) in sea water due to rather small attenuation of EM signals, with range decreasing by 1/e every 270m at 1Hz and also as the square root of the frequency. This is in close

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agreement with our experimental scenario for the source of “reality matching” pulses to test the computational proposal. The authors even explored the practicality of lithospheric communication, obtaining sufficient signal/noise ratios but at 100 km ranges and 1 Hz bandwidths. Again, even through the under seabed crust, lower than 1 Hz waves can convey information at distances up to 100 km. It is obvious that before we talk about the feasibility of sea water propagation, lithospheric propagation has to occur, especially for the scenario used in the typical 20-60 km depth hypocenters in the subduction zone along the Peruvian coast. For magnetometer coils buried at the sites, several kilometers from the sea shore, the all-lithospheric propagation of the ULF pulses is a very plausible scenario. As you can see, we in Peru, are using Dr. Freund’s positive holes theory to understand the underlying phenomena of charged particles and electromagnetic pulse generation as related to premonitory seismic activity. Even more, we are using it to predict the occurrence of earthquakes and their possible epicenters and complying in every case with reality. In summary, I believe that the model described in our paper explains very well the production of ULF pulses, embedded in reality as evidenced by the “predicted” earthquakes in central and southern Peru.

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