VOLTAGE BUILD-UP MEASUREMENTS OVER DIFFERENT ROCKS DURING UNIAXIAL COMPRESSION TESTS

MEDICIÓN DE VOLTAJES EN DISTINTAS ROCAS DURANTE ENSAYOS DE COMPRESIÓN UNIÁXICA

Julián Peláez Quiñones [1]*; Erick Mora Martinez [2]; Andrés Picón Garcia [1] & Jenner Varón Bernal [2]

[1] Geology student, Geosciences Department, Universidad Nacional de Colombia. Bogotá
[2] Electrical Engineering student, Engineering Faculty, Universidad Nacional de Colombia. Bogotá
** Contact information: Julián Peláez - jdpelaezq@unal.edu.co. Bogotá, Colombia*

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Resumen

La presencia de fenómenos electromagnéticos inducidos por procesos mecánicos sobre ciertos materiales ha sido ampliamente estudiada desde el descubrimiento de la Piezoelectricidad a finales del siglo XIX. En la actualidad existe una amplia gama de modelos físicos aún en debate respecto a las observaciones de estos fenómenos en rocas y otros materiales terrestres, además de persistir controversia en relación a sus posibles aplicaciones en Sismología.

En un intento por explicar la presencia de fenómenos electromagnéticos asociados a la acumulación de esfuerzos mecánicos en la corteza terrestre, los científicos han recurrido a diversos mecanismos, tales como: el Piezomagnetismo y la Piezoelectricidad; el Efecto Magneto hidrodinámico; la Triboelectricidad; el efecto Electrocinético; Microfracturamiento y el Efecto Semiconductor, debido a la migración de vacancias positivas en rocas silicatadas a través de un gradiente de esfuerzo, entre otros.

En este texto se pretende exponer brevemente el estado del arte del estudio de estos procesos, así como generar una breve discusión en cuanto al problema y finalmente mostrar el desarrollo y resultados del experimento central realizado: Pruebas de compresión uniáxica sobre rocas de litología variable y medición de voltajes inducidos entre los extremos de las mismas por la fuerza aplicada.

Se discutirán, principalmente, detalles experimentales en relación a este tipo de ensayos para poner a prueba la validez de las mediciones obtenidas y se compararán nuestros resultados con los de otros autores. Estos ensayos están ampliamente basados en experimentos previamente reportados en la literatura (Freund 2003; Takeuchi *et al.* 2006, etc.) y se llevaron a cabo en los Laboratorios de Ensayos Mecánicos de la Universidad Nacional de Colombia en Bogotá entre los meses de Septiembre y Octubre de 2014.

***Palabras clave**: Compresión uniáxica de rocas, Voltajes inducidos mecánicamente, Procesos sismogenéticos, Propiedades físicas de materiales terrestres.*

Abstract

The presence of mechanically-induced electromagnetic phenomena on certain materials has been widely studied since the discovery of Piezoelectricity by the 19th century, nevertheless, at present debate persists in relation to the physical mechanisms underlying this type of phenomena, especially when it comes to observations made on rocks and other earth materials. Moreover, a great deal of controversy arises when it comes to their possible seismological applications.

In the present text, we intend to show the development, results and final thoughts regarding a set of experiments of uniaxial compression and related electrical potential difference measurements over different types of rocks, which we performed on the basis of previous tests reported in the literature (Freund 2003; Takeuchi *et al.* 2006, etc.).

Our goal is to put this kind of experiments to the test, mostly by debating experimental details, from the internal state of the tested rocks (weathering, mineralogy, and so on) to the external sources of noise likely to affect the measurements. We will discuss and compare our results with those of other researchers. Additionally, and by way of compilation, we will mention the basics of some of the mechanisms proposed by different authors to explain the presence of electromagnetic (*EM* from now on) phenomena possibly associated to the natural build-up of stresses in the Earth's crust. These include: Piezomagnetism and Piezoelectricity; Magnetohydrodynamic effect; Triboelectricity; Electrokinetic effect; Microfracturing and the sometimes referred to as *Semiconductor effect*, due to migration of positive charge vacancies (peroxy defects) in silicate materials under a stress gradient.

Keywords: *Uniaxial Compression of rocks, Seismogenetic processes, Stress-induced voltages, Pressure-stimulated currents, Physical properties of earth materials.*

INTRODUCTION AND THEORETICAL FRAMEWORK

The motivation of the present report relies on the extensive studies by many researchers around the world regarding Earthquake-related phenomena, aside from seismic waves themselves, which have been studied and characterized in detail by seismologists since many decades ago, and comparatively little interest has been given to other kinds of phenomena that may be related to the process of natural "Earthquake preparation". The study of these "other kind of phenomena" dates back to the decade of 1970 (and even before), where some of the first reports can be traced (Derr 1973; Kerr 1978). Since then, an increasing number of papers account for observations, experiments and possible explanations for such phenomena, most of them related to natural-occurring telluric currents (Bobrovskiy 2010; Freund 2003; Uyeda *et al*. 2009; Zhao & Qian 1994); anomalous magnetic fields (Fraser-Smith *et al*. 1990; Serebryakova *et al.* 1992; Scoville *et al.* 2014); anomalous EM waves: Infrared, Radio, visible light (Biagi *et al.* 2001; Derr 1973; Kamogawa *et al.* 2005; Qiang *et al.* 1991); atmospheric and inospheric perturbations (TEC, thermal anomalies) (Akhoondzadeh *et al.* 2010; Dunajecka & Pulinets 2005; Gousheva *et al.* 2008; Liu *et al.* 2004); massive air ionization (Bleier *et al.* 2009; Hattori *et al.* 2008); apparition of cloud patterns above epicentral areas (Guangmeng & Jie 2013; Ondoh 2003); chemical variations in atmosphere and hydric sources (İnan *et al.* 2008; Moura *et al.* 2011); anomalous animal behavior (Hayakawa 2013); Ground deformation (Bella *et al.* 1995); processes which allegedly can be detected before (generally referred to as *Seismic Precursors*), during and after strong earthquakes ($M \geq 5,0$). These are just some examples of the amount of information available which, although widely questioned and criticized by the seismological community, will only be understood and determined valid or void through objective and systematic study, experimental and theoretical (e.g. see Johnston *et al.* 2006; Wyss 2001).

There are diverse hypotheses trying to account for the origin of electrical currents generated through rocks and triggered by mechanical agents. Scientist Friedemann Freund relates this process to the sometimes referred to as the *Semiconductor effect*, which would explain stress-induced current over silicate-rich rocks (the most widely distributed in the earth) and which relies on the existence of peroxy defects (Si-O-O-Si), where the oxygens have a (-1) valence, within a "normal" silicate matrix (Si-O-Si) with oxygens bearing a (-2) valence and are, therefore, way steadier; the peroxy defects thus have a positive hole pair, two positive vacancies respect to the matrix's stable oxygens. This peroxy links are easily broken when intercepted by dislocations in the crystalline network of minerals constituting the rocks when subjected to external stresses, which would trigger a migration of these positive holes under a stress gradient in its decreasing direction and is equivalent to negative charges flowing in opposite direction to complete the (-2) valence of the immediate neighbor oxygen (Freund 2011). The flux of positive charges would generate a current capable of reaching earth surface and even ionize the air in air-ground interface, which in turn could generate ionospheric anomalies if a large enough mass of air is ionized in the atmosphere; this could also explain anomalous electrical and magnetic fields linked to earthquake-related EM signals; *Corona* effect; seismic clouds and even local variations of water pH if positive charges come in contact with it.

The biggest conceptual difficulties of *Semiconductor effect* are that the existence of tridimensional stresses at depth has not yet been taken into account, experiments have only been performed with uniaxial loads; the recreation of physical and chemical environment at depth is partial and there's not clarity regarding the way the "geological circuit" necessary to generate the observed anomalies would be closed in real environment, a possibility for the completion of this circuit is through electrolytically conductive water, which is not necessarily present at great depths owing to lack of rock permeability, even though magma bodies and fault/fracture families could allow the process.

Another idea is that air ions over epicentral areas, or the deep crust, which is electrically conductive (n-type) could close the circuit proposed by F. Freund. It is also not clear what process could regenerate these peroxy defects in the rocks of a recurrent seismogenetic zone after each event through time.

The experimental set-ups of *Semiconductor effect* proponents have also been questioned due to possible reported measurements of surface potentials and not phenomena inside the rock itself, further on, other facts of experimental nature regarding the acquisition of data might make the reliability of previously reported results tremble.

Piezoelectricity is another possible explanation of subterranean currents related to earthquakes but, due to the fact that piezoelectric mineral's crystallographic domains in rocks are not always aligned, it has been called into doubt as a major contribution; moreover, around half of the quartz (principal and most abundant piezoelectric mineral in the lithosphere) present is levogyre and the other half is dextrogyre, which means they have opposite piezoelectric domains and, if aligned, their electric fields would cancel out. Electrokinetic effect has been proposed to explain ELF and ULF signals when conductive fluids flow through permeable rocks, but igneous and metamorphic rocks have very low permeability and at more than 5-7 km depth, rocks loose porosity owing to the high lithostatic load they are under. Flux potentials are also very sensitive to dissolved salts in water, increasing conductivity and generating voltages too small to be detected in surface (Freund, 2011).

Microfracturing, which would generate electrical charge separation is hard to prove valid at seismogenetic depths (15-40 km) due to lithostatic load in these zones; the same argument could be valid against Magnetohydrodynamic effect owing to flow of briny liquids in presence of magnetic fields. Piezomagnetism is observed in some antiferromagnetic crystals like Goethite and Atacamite, which are typically found near the surface, but only Pyrrhotite could be found in rather specific zones in seismogenetic depths and its non-aligned domains would cancel the total magnetic field (Freund, 2011).

Triboelectricity between surfaces in contact at depth could also in part explain EM anomalies, but some authors claim that it is hard for this effect to be significant in fault zones, which are, apparently, quasi-static (Leeman *et al.* 2014).

All of the mentioned phenomena could contribute at least in some specific environments to the anomalies mentioned before, or these could even be the result of a superposition of more than one of the proposed mechanisms. Their weight and detailed developing environment is yet to be determined.

METHODOLOGY AND EXPERIMENTAL BACKGROUND

Our experimental set-up represents a simplified model of the complex tectonic stresses build-up process in the earth and it is widely based in those performed by Friedemann Freund (2000, 2006, 2011, 2013), amongst others (Balk *et al.* 2009; Batllo *et al.* 1990; Takeuchi *et al.* 2006; Takeuchi & Nagao 2012; Triantis *et al.* 2006).

The former, tests rocks by compression in uniaxial constant stress rate mode over different types of igneous rocks (Gabbro, Basalt, Granite, Anorthosite) using axial universal testing machines. In our case, compressive tests were performed on Aplite, Basalt, Migmatite and Marble samples collected from the surroundings of Cepitá, Colombia, in the Santander Massif area. F. Freund reports currents up to 20 nA for constant stress loading over Gabbros with maximum static stresses around 50 MPa and surface potentials of 3V in the process. Takeuchi & Nagao (2012), report EMF's up to 80mV, while similar experiments with different materials report over 20V (Leeman *et al.* 2014). The basis of the experiment (in the framework of previous analyses by the authors mentioned) is that while mechanically loading a rock sample in one of its extremes, it will act momentary as a battery by charge separation (negative charges would concentrate in loaded extreme and positive charges would flow to unloaded zone). We attempt to measure this potential difference between loaded and unloaded extremes of prismatic rocks (Dimensions: ≈ 30x15x15 cm^3) and characterize its behavior while being subjected to approximately linear stress build-up. Two electrodes where placed in each extreme of the smooth surface of rock (Copper side of Bakelite and, in some tests, with Copper tape) and the coaxial cables and contacts (welded with tin) where wrapped inside aluminum foil.

With the available tools and equipment we measured potential difference using *LeCroy* Waveace 101 (working frequency: 40 MHz; sample rate: 500 MSa/s) and *RIGOL* DS1102D Oscilloscopes (wf: 100 MHz, sample rate: 500 MSa/s; range: 2 mV/div - 10V/div). Coaxial cable (R-6; 0,75 Ω; 90% braided) from the rocks to the Oscilloscope was used and an aluminum cage of 2 mm-diameter slits worked as a Faraday cage for the rocks under test in order to isolate rock from external EM fields. Two loading machines were used: Electro-mechanical *Shimadzu* UH-I uniaxial 500 kNI and Electro-hydraulic Universal testing 30 ton *Amsler*. The equipment belongs to the laboratories of National University of Colombia in Bogotá. Data was acquired through USB from Oscilloscopes to computer using "*Ultrascope* DS1102 *RIGOL*" Software. **(Figure 1)** shows the experimental set-up.

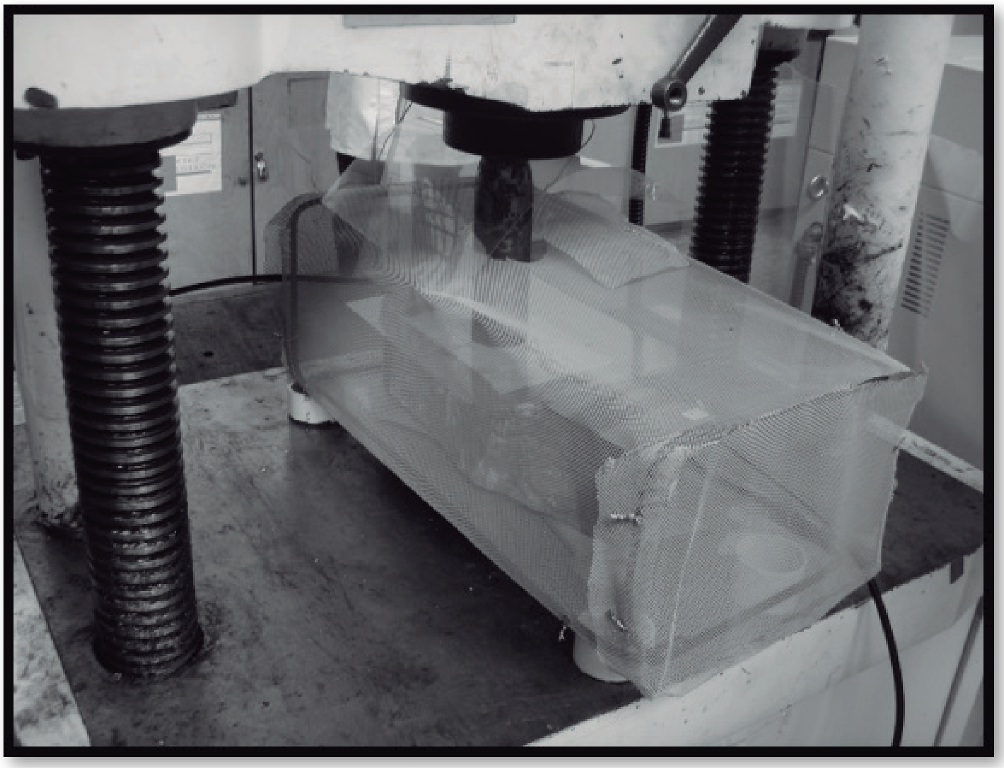

Figure 1. Photograph of first test with Marble (deformation rate of 0.5mm/min). In subsequent experiments the rock was compressed along with the Faraday cage to avoid entrances for external EM noise.

The compression loading rates were between 0,5 and 0,8 mm/min of approximately constant displacement of the machine's piston (*Constant strain rate mode*) when *Shimadzu* UH-I machine was used (for an Amygdular Basalt and a Foliated Marble); and were nearly at constant stress rate mode when the *Amsler* machine was used, but due to the fact that *Amsler* machine is Hydraulic and works through manual valves, it is difficult to keep its rate fixed. For the first two rocks (Basalt and Marble) a 10x10x0.5cm^3 Copper Bakelite was located directly over the rock, and for the remaining ones, Copper tape (thin laminae) was used for improving the contacts with the rock.

RESULTS AND ANALYSIS

1. *EMF (electromotive force) in Basalt and Marble under uniaxial loading*

A cylindrical piston of 2'' (2,54 cm) diameter was used along with a Faraday cage with superior and inferior holes for the pistons to contact the rocks. The voltage tendency was not clear in the Basalt test because of EM background noise ($f \approx 2$ - 60 MHz; $V_{max} \approx 30$ - 150 mV) in the laboratory; although a subtle increase in the signal (of alternate nature) was observed during the compression (a total increase of ≈ 8 mV). A subsequent test showed a maximum voltage V_{max} ≈ 100 - 230 mV (increase of ≈ 70 mV), but this could be related to an increase of voltage in compression machine, or even to a sudden charge separation because of microfractures formation or dislocation of microfault planes (Freund 2011), that generate transient voltages.

It is reminded to anyone trying to recreate this type of tests to avoid the use of non-shielded (for Electric fields) conductive cables outside Faraday's cage (which would be antennas for external EM signals), and also to avoid forming any semi-closed loop with the measuring cables, which would allow the flux of magnetic fields that could generate undesired currents through the cables (this was probably a source of noise in these tests). A big-scale Faraday cage can also serve to isolate external EM fields, but, of course, not those of any electrical devices inside the cage. To isolate pistons from the rock, linoleum and vinyl acetate laminae between them were used; nevertheless, displacement currents transmitted from the machine to the metallic piston cannot be effectively isolated and a great deal of alternate noise is detected.

For the Marble tests (f ≈ 2 - 60 MHz; V_{max} ≈ 40 - 152 mV) a subtle increase of no more than 80mV in voltage signal was observed during loading; but, again, one cannot discard its origin from the machine itself, which during increase of the force (and the power consumed) that applies over the material could require higher currents in its internal circuits in order to keep the strain rate constant. **(Figure 2)** shows the displacement of the machine head for a constant strain rate mode for Marble tests.

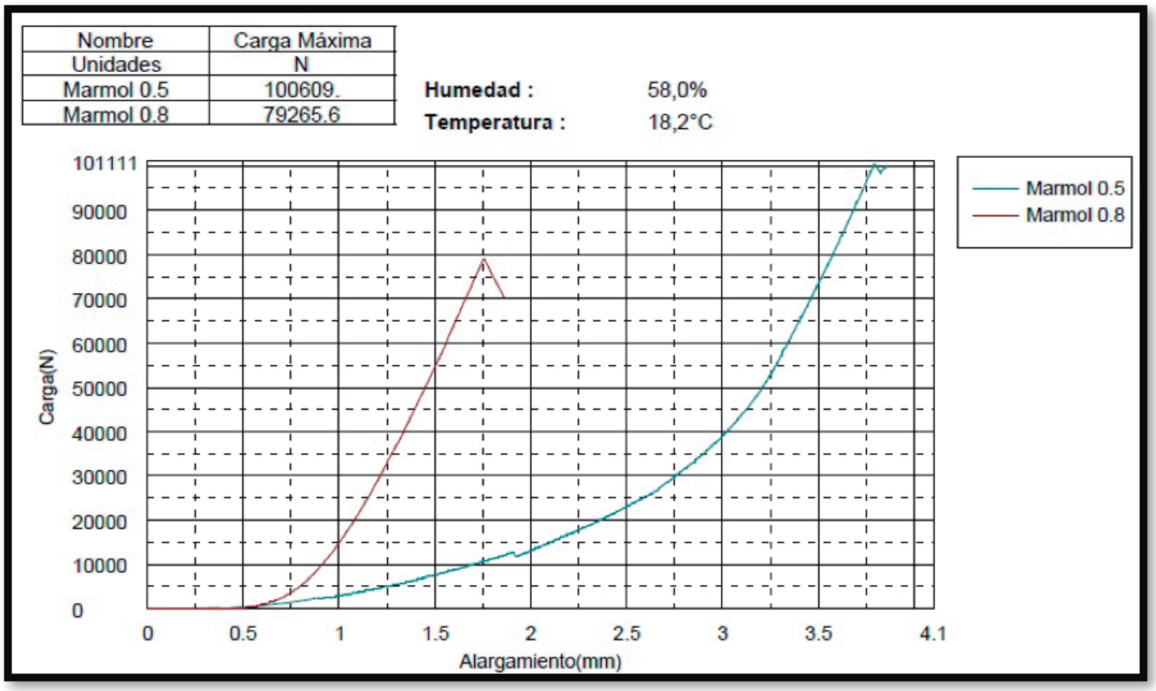

Figure 2. Graph of displacement of machine head (strain) against force applied by the machine. The use of a 2'' (2,54 cm) diameter piston accumulated the stress around a small area, and allowed an easy failure. Red: displacement rate = 0,8 mm/min. Green: displacement rate = 0,5 mm/min.

No considerable improvement of measurements is achieved when enveloping Faraday's cage in aluminum foil or putting more acetates in between rock and piston. The coaxial cable itself did not improve the results significantly in this test. In the first test with the Marble, some 39MPa (10 tons with the area used) were reached, and in a following test with the same rock it lost internal cohesion and could only withstand approx. 7,5 tons before fracturing, because of fatigue after the generation of internal and external microfractures in the first attempt, as expected.

2. EMF in Aplite under uniaxial loading

For the Aplite sample (*Dim*: 5x9x20 cm^3), Amsler 30 ton electro-hydraulic machine was used along with a *RIGOL* DS1102D Oscilloscope. The cables were jointed to avoid loops and the Faraday cage was improved by sealing it almost completely removing the holes for the piston to break through, and therefore the rock was loaded along with the cage. In order to avoid possible surface potentials in the rock, insulators were located between the cage and the rock inside. The coaxial cables were jointed and inclusively put inside an aluminum wire mesh and contact electrodes with the oscilloscope wrapped inside aluminum foil. *Banana* connectors and probes made part of the wiring system. A cylindrical metallic piston of 11,4 cm diameter was employed and, due to its larger diameter compared to the samples, there's uncertainty in estimating stress over the rocks. The data recording rate through computer is about 1Hz.

Amsler machine performed at its minimum speed, but being manually controlled by valves, it's hard to determine its total strain or stress rate, which are not constant during the test. There was a noticeable gradual fracturing of the sample and an increase in voltage was detected with $|V_{max}| \approx 23$ mV, superposed with background noise. In comparison with previous tests, ambient noise was reduced at about 80%. Peak-to-peak voltage increased from 10 mV, up to more than 40 mV, in the first 8 minutes of loading. Black vertical lines in **(Figure 3)**, mark beginning and end of loading at nearly constant stress rate different from zero; the last minutes indicate fixed static load. After applying approximately 15 tons of load, voltage decreased drastically (this could be correlated to a moment of fracture propagation) and the final signal, after a fast increase of load up to 20 tons, showed a low amplitude (5mV) in comparison with the rest of the test. The last 6 min. (static load) don't show signal variations and the noise remained; the rock was already fractured before reaching a maximum of 25 tons.

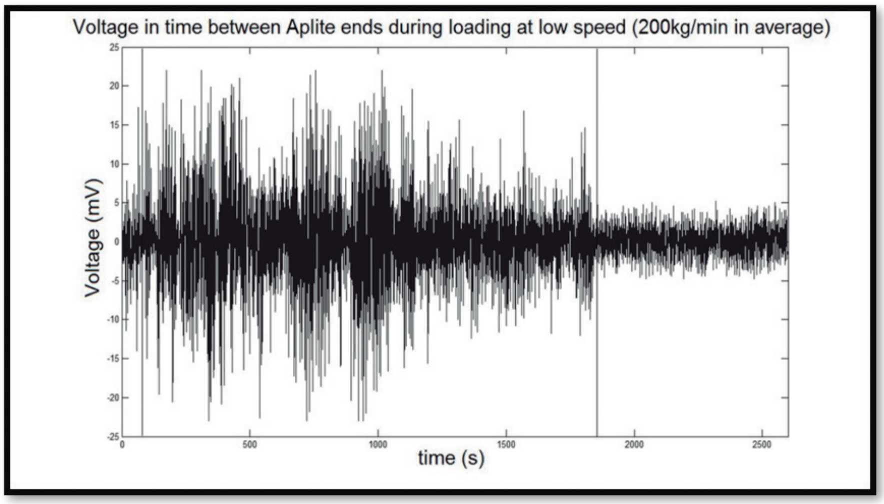

Figure 3. Voltage in time for loading of Aplite at low speed (≈ 1960 N/min) and nearly constant. Data recording rate was about 1Hz and total time is about 40min. The two vertical lines indicate beginning and end of loading at constant rate different from zero; during the last minutes, the load was sustained after visible fractures were generated but before the rock lost its assembling cohesion. Scale's maximum is 25 mV; minimum is -25 m.

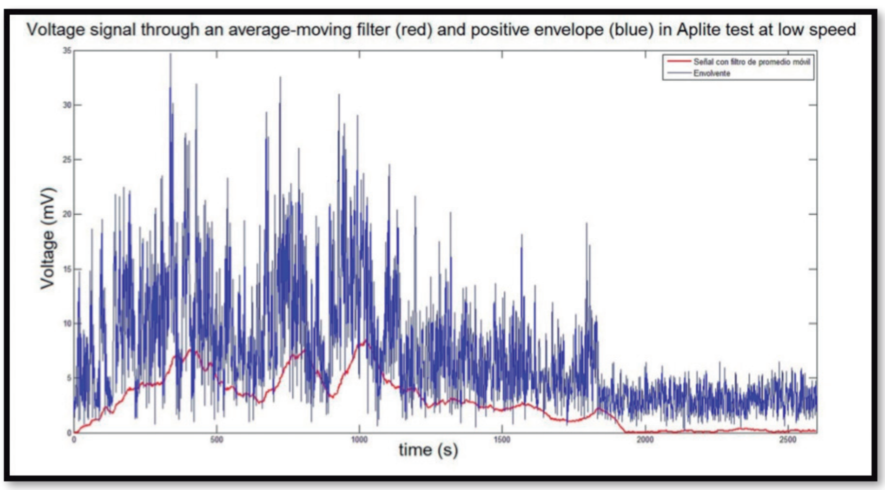

Figure 4. Graph of voltage in time domain with the processed signal through a moving average filter with 100s interval (red) for the Aplite loading test (Figure 3) at low speed (≈1960N/min) and nearly constant. Envelope of the signal (absolute) is also included (blue) to observe the behavior of the raw data. Scale's maximum is 35 mV; minimum is 0 mV.

In order to better visualize the behavior of the raw recorded signal, a graph of it after passed through a moving average filter with 100s interval and corrected delay **(Figure 4)**, which show the mean tendency of the signal and decreases noise effects, but with the disadvantage of losing the original measured amplitudes. The positive voltage envelope in time is also included in **(Figure 4)**, and it preserves better the amplitudes but is heavily influenced by ambient noise and anomalous peaks.

3. *EMF over Migmatite without load during uniaxial compression test over Marble –"Noise Test".*

The main goal of this test was to probe whether the tension measurements in the previous ones can be attributed to a phenomena "inside the rock", that is, an answer to charge separation through the rock, related to the applied load, or simply due to EM noise coming out of the electrical motor of the Universal *Amsler* 30 ton machine (or any other source). For this purpose, voltage was measured in a total time of 45 minutes between the extremes of a Migmatite with Leuco- and Paleosome lying "free of stresses" while a compression test was carried upon a Foliated Marble in the same room, and placing the Migmatite inside the Faraday's cage a distance to the electrical motor nearly equal to the distance between the pistons and the motor of the machine itself. The first noticeable fractures occurred between 4 and 10 tons of load, and they apparently propagated in stages during the test. The rate of compression of the machine was intermediate (≈ 528 kg/min) and was not uniform, but accelerated in stages and presented abrupt increases of stress, although it was linear in average. Maximum load was 25300 kg, that is, around 24 MPa, and corresponded to the maximum cohesion stress of the sample, where it was torn apart. Ambient noise was recorded since the beginning of the measurement (first 5 min.) with the machine on, and at the end of the test, when it was shut down (last 2 min.). **(Figure 5)** shows unprocessed (raw) signal.

Our intension was to be able to detect an increasing voltage signal coming out of the machine while the rock not subjected to stresses. On the day of the test the weather was rainy, thus contributing to a higher background signal and higher peaks in comparison with earlier tests (Δ noise; Vmax ≈ 55mV in "noise test" against Δ ≈ 15mV in previous test with Aplite in dry conditions). Amplitude of detected noise is around 100 ± 5 mV. Its frequency is high (1 - 2MHz detected by oscilloscope), and it was not possible to analyze it with Fourier methods because of a very low data sampling frequency (50Hz); and adding it up a number of times didn't improve the signal. For the purpose of enhancing the visualization of data, envelope (absolute value of analytic signal through Hilbert transform of raw signal – inaccurate because of low sampling rate and noise in raw data) was comprised along with a moving average filter with corrected delay and 50 samples interval. These synthetic signals are alterations of the original data, but allow us to observe general tendencies of measurements and to detect peaks and anomalies easily. The peak around 900 seconds in **(Figure 6)** corresponds to an experimental error caused by experimenters during the test.

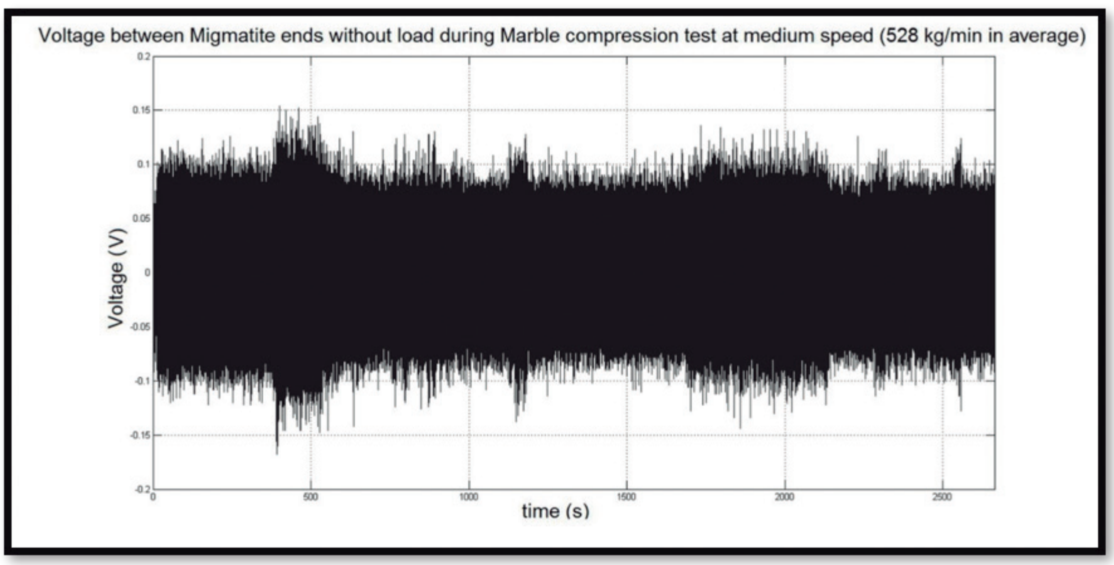

Figure 5. Graph of voltage in time (raw) between extremes of Migmatite during loading of a Marble at low speed (≈ 1960N/min) and nearly constant. The signal presents a great deal of ambient noise hard to eliminate due to the low sampling frequency of data in relationship with the high frequencies of the signal ($f_{sampling}/f_{EM\ noise} \approx 5x10^{-5}$). Fourier analysis could not be carried out. Scale's maximum is 0,2 V; minimum is -0,2 V.

(Figure 5) shows, apparently, that during fracturing stages of marble, peaks in voltage are generated in short periods (50-60 seconds), and even though they could be related to sudden charge separation, they could also correspond to the machine internal electrical operation. **(Figure 6)** represents the raw data of **(Figure 5)** with moving average filter applied and with positive envelope. Around 400s a first increase in the signal reaches 150mV and decays almost linearly in some 3.5 minutes. After this, there are other two maxima, the first of them is lasting and shows a slow increase and a relatively fast decrease, the other increases similarly to the first one but is better defined, shorter and decreases abruptly. At 1600s, maximum voltage increases symmetrically and lasts between 8 and 9 minutes, presents some anomalous peaks of up to 140 mV, and its form is somewhat different from the previous. At the end of the signal there are two peaks similar to the second and third mentioned before, with a gradual increment, abrupt decrease and lasting 40-60 seconds; the last one coincides with the moment of strong failure of the rock that lead to a sudden fall of stresses and marked the end of the test.

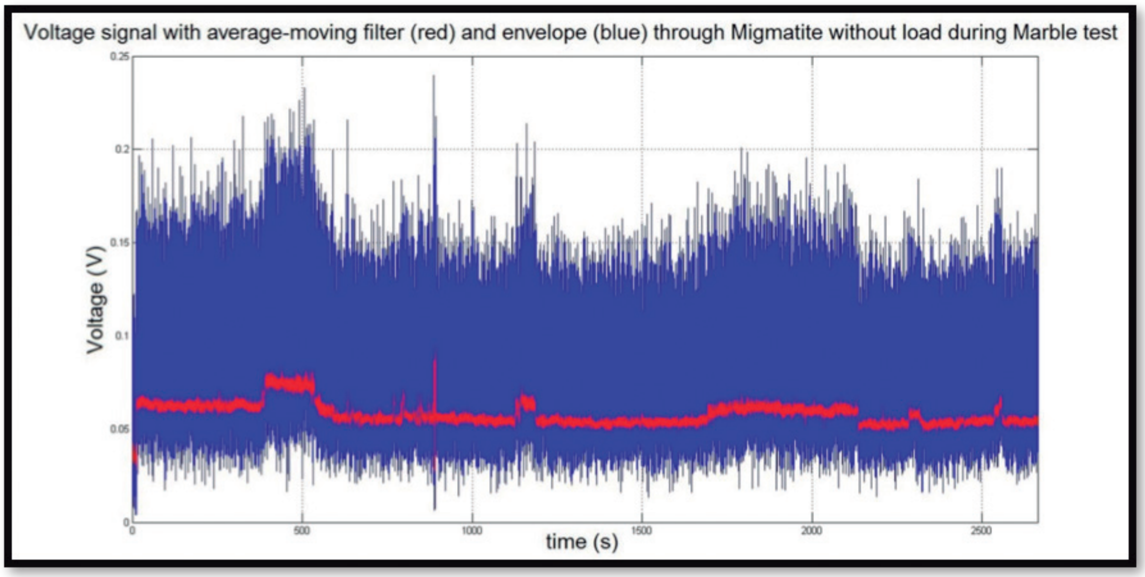

Figure 6. Graph of voltage in time for "Noise test". The data was filtered with a moving average filter at 50 samples interval (red) for Marble loading at medium speed (≈ 5175N/min in average). The magnitude of analytical signal of raw data (blue) evidences general behavior of signal. Scale's maximum is 0,25 V; minimum is 0 V.

It is hard to assert whether the voltage fluctuations derive from the machine; an electro-mechanical phenomena in the rock, or some other external origin; a first impression could lead us to believe that propagation of EM noise out of the machine underlies the results, and we have, thus, to take into account the internal functioning of the machine. Electro-hydraulic machines operate through an electrical motor, which transforms electrical energy into mechanical energy, and which, in turn, remains coupled to an hydraulic pump, which converts the mechanical energy into kinetic or potential energy of a fluid (oil) to finally result in mechanical compression when it is displaced. According to Khaimovich (1965, p.266), mechanical motors of electro-hydraulic machines can vary their rate of force during their use, and moreover, the hydraulic pumps, with their valves system, when de-accelerated present inertial forces upon the machine head (table) that increase the pressure in the suction zone and generate a torque in the pistons, whereupon the pump is accelerated (and acts as a motor), in other words, variations of speed of the pump could generate variations of speed in the electrical motor. This is reaffirmed in *the Great Soviet Encyclopedia* (1979), wherein it is asserted that Electrical AC motors vary the speed of their rotor in response to the mechanical load applied over the operator mechanism. However, it is not discarded that the obtained signals come out of the compressive stimulus over the rock, provided that the Marble subjected to uniaxial loading wasn't isolated with a Faraday cage.

GENERAL DISCUSSION

Oscilloscopes are not the most appropriate measurement instruments for long-time intervals, high sampling rate and high resolution necessary for the kind of phenomena we intended to detect through these experiments, but they can be partially useful for a general acquaintance. The increase in voltage measured between ends of rock under pressure was ≈ 10 - 70 mV; the two principal suspected sources are: EM noise coming out of the electrical motor of the universal testing machines used or PSC (*Pressure stimulated currents*) phenomena through the rocks.

During the Aplite test, voltage fluctuated a lot and a very low modulating frequency ($f^{-1} \approx 150$ s) is superposed over the higher EM frequencies, this behavior can be related to gradual fracturing stages, but in general, an increase in electrical potential difference was detected, followed by a gradual decay overloaded with alternate noise that could come from the triphasic motor (*A.G. Brown, Boveri & Cie.* - 250V; 8,5A; 2,6kW; 60Hz) that powers the *Amsler* electrical-hydraulic machine. The increments could also be associated with internal phenomena in the rock and subsequent fractures with potential difference decreases. The signals tend to show abrupt increases and smooth decreases, a detailed knowledge about the characteristics and internal operation of the motor is required, and primarily, understanding the dynamic of the *motor-machine-sample-material* system to assert about the correlation between signals and motor. The "noise test" showed considerable noise and higher voltage peaks compared to the other tests, in part this mismatch respond to the difficulty of recreating the set-up over and over, and monitoring ambient external variations (rainy days, electrical network perturbations, random sources of noise). If the machine is a source of the signal, the difference between maximum voltages (± 20 mV for Aplite test against ± 140 mV for unloaded Migmatite – "noise test") could be due to the different geometries of the samples; different cohesion, sutured contact between grains and compact crystalline network, so that the power required to compress the Marble was higher; even though the Marble sample showed a higher grade of weathering in comparison to the Aplite. If the rocks are sources of PSC, it wouldn't be in agreement with Freund model of silicates (composition of quartz that make up the Aplite) generating the anomalies, which were higher in the Marble (mostly made-up of Calcium and Magnesium carbonate), nor with piezoelectricity, which would be exhibited by quartz, not by dolomite or calcite. Triboelectricity or microfracturing seem more likely to be responsible for the signals, at least in our experimental conditions. A mixed origin of the EMF's is also possible; moreover, an unequal superposition of the principal evidences mentioned above is not excluded.

The measurements present a clearly low signal/noise ratio, i.e. saturation with ambient noise, which wasn't possible to remove with the known processing techniques because of the low sampling frequency available ($f_{sampling}/f_{EM\ noise} \approx 5 \times 10^{-5}$). The determination of groups of frequencies by Fourier analysis would have been very useful to separate characteristic signals from specific sources, for example, the electrical motor, some EM waves, or low frequencies linked to quasi-linear increments and decrements, but wasn't possible. In relation to the coincidence of fracture moments with voltage peaks, it can be said that the charge separation process would generate high frequency signals (Freund 2011), quite different from the radio (low frequency spectrum) EM signals allegedly related to seismogenetic processes that are the most reported through the literature, due to the higher absorption of small wavelengths by the rocks of the earth's crust. It's unclear whether there is a sort of retro-feeding system in the loading machine internal system and the rock under pressure, nevertheless, it's interesting to note that some of the electrical responses were almost immediate when fracturing the rock, which could complicate the hypothesis of Motor as main source of voltage peaks, owing to an expected delayed time of response of the hydraulic-electric system, but by no means discard it; as said before, more detailed knowledge of hydraulic machinery is necessary.

According to results, a correlation between the loading and fracture of the rocks and the voltage increments should exist; nonetheless, the challenge resides in proving that these signals do actually "come out of the rocks", and moreover, if those EM signals reported before Earthquakes "come out of those rocks involved". The increment of peak-to-peak voltage as an alternate signal increasing its amplitude; the recording of a maximum voltage during "Noise test", even higher than the one recorded in direct loading tests; and the existence of external sources (i.e. the electrical motor; measurement instruments or unconsidered sources) lead us to think that the detected signals in our case are product of undesired external noise, not from the rock itself.

The AC character of the measurements are, in part, due to the AC coupling working mode of the oscilloscopes, that tends to eliminate or transform DC signals to AC. There are heterogeneous forms of increments of potential difference, some are short and with abrupt decay, some are lasting and steady, and there's at least one with abrupt increase and smooth decay, which lead us to suspect more than one generator phenomena alone. Some mismatches between tests can be due to irregular electrodes contact with the rock, unreproductable background noise or different properties of each rock. Takeuchi & Nagao (2012) report voltages of more than +80mV in similar tests with Gabbros, an intermediate value between the 25 and 150mV (amplitude) detected in our last two tests, which shows at least some level of agreement. Freund *et al*. (2006) report electrical currents of 1-2 nA in rocks, which, according to the geometry of the rocks used and the average voltages measured in our case, would lead to a rock resistivity of nearly 2 x 10^6 Ω m, in agreement with common igneous and metamorphic rocks resistivity values, that range between 10^2 - 10^8 Ω m.

From our point of view, F.T. Freund's ideas in some of his papers (2006, 2011, 2013) have a good theoretical support and apparently good experimental results, but after trying to reproduce his experiment, we question the insulation conditions of his experimental set-ups, more specifically when it comes to EM noise generated from the loading machine, taking into account that we are not aware of reported tests to measure of to filter its noise or any other generated by external sources. Nevertheless, we remind the reader that our tests are merely a first attempt of reproduction of PSC tests with the tools we had available and must be improved philosophically and in terms of infrastructure.

From a geological point of view, it seems very important to have access to unweathered rocks obtained from wells or zones of mild weathering conditions (contrary to those commonly found in surface conditions in Colombia). According to Chamberlain, P.G. *et al.* (1976) and Haimson, B.C. (1978), all the processed the rocks are subjected to after exhumed from depth (hydration, fluid depletion, cyclic load-unload; fractures, weathering, etc) may alter their internal properties, as ultimate stress; Elastic-mechanical properties; anisotropy; among others, which puts into test that mechanisms as Piezoelectricity or Semiconductor effect are the principal generators of EM earthquake precursors, and opens the possibility that triboelectricity, microfractures or electrokinetic effect are significant at surface level, when performing testing experiments. Minerals with electric and magnetic properties do exist, examples are: Quartz; Magnetite; Pyrrhotite; Iron-bearing minerals and Metallic ores, but the extent up to which their piezoelectricity, piezomagnetism or conductivity may contribute to EM seismic precursors is yet to be concluded. Plenty of research and compilations as those carried by Bobrovskiy (2010); Cicerone *et al.* (2009); Jhonston (2007); Smirnov & Zabyalov (2012); among many others already mentioned and others not included, seem to lead to the fact that certain correlation between seismogenetic and natural Electromagnetic phenomena exist, even though being an apparently complex and controversial topic, we consider that it must not be ignored but addressed in a rather objective manner and studied in depth, owing to its puzzling nature and possible applications in geophysics.

We end our discussion by stating that fluxes of positive vacancies from seismogenetic zones to earth's crust surface appearing in moments of failure of tectonic stresses, although possible, may be an oversimplification, on account of the real complexity of rocky materials, which, even down in a Petrographic microscope, can be seen to wear a broad range of micro-characteristics like porosities; shally matrix; organic matter; pore-fluids like water with variable salinity and hydrocarbons in the case of sedimentary rocks, and altering hydrothermal fluids; trace elements; fluid inclusions; special textures (grain size and grain contacts), in the case of igneous and metamorphic rocks, that could, in turn, hinder the charge migration process. Previous models tend to think the earth crust as a homogeneous media, but physical interfaces of different type: inertial; elastic; compositional; crystallographic anisotropy; and structural (for example, joints) could affect the migration process from hypocenter depths (typically 5-200 km) to the surface. Our future intension is therefore, to continue with efforts to take the geological perspective into account in these models along with the chemical, physical and mathematical point of view.

CONCLUSIONS

- Measurements of electric potential difference between extremes of (almost) prismatic samples of lithological variable rocks obtained in outcrops with sub-aerial exposure, during uniaxial mechanical loading at nearly constant strain rate over one of their extremes, gave rise to a voltage signal that, on average, increased in the first moments (less of about the first half of each test, from load ≠ 0 to maximum stress applied) and decreased its amplitude over the rest of the course of each test, taking as a level of reference the ambient noise voltage **(Figures 2,3,5,6)**. The increments of voltage disappeared at the end of each test (no load over the rocks) and while sustaining static load over the samples.
- The obtained voltage signal was of alternate type and its amplitude fluctuated over the course of the tests, producing peaks and local decrements, additionally to the general tendency explained

above. All increments were symmetric about time axis, which may denote: 1) Increasing alternate background signal (noise) that is possibly related to the Universal testing (loading) machines used; 2) Direct signals coming out of the rocks, superposed with alternate ambient noise and/or transformed into alternate signals by Oscilloscope itself operating in AC coupling mode, which removes DC components and only allows AC visualization. It is not trivial to affirm that the rock would generate AC signals when subjected to linear stresses; or 3) Superposition of aspects 1) and 2).

- The electric and magnetic insulation proceedings succeeded in diminishing ambient noise and allowed to detect a changing EMF time-signal which, in turn, suggests good correlation between failure and voltage peak instants, but this is only apparent (exact moments of failure could not be recorded). Unfortunately, few tests could be conducted (6 in total) and therefore our experiment lacks of statistical rigor, but our results show at least partial agreement with other authors' voltage trend and maxima results in similar experiments. We question, however, the noise insulation conditions of other tests reported in the literature that would allow ruling out external sources as generators of voltage increment measurements over progressively stressed rocks (see General discussion).

SOME RECOMENDATIONS AND FINAL THOUGHTS

In relation to the experiment here presented, it'd be interesting to vary and have control on the variables here introduced and others not considered, to study their separate behavior and weight on the results; for example, lithological variables as: mineralogy, type and grade of rock metamorphism, usage of mono-mineral, sedimentary, water content, and different weathering state rocks, etc. The geometry and type of stresses (tensional, multi-axial, areal, etc.) in the tests could also be modified, along with the rate of stress and parts of the test material between which voltage and/or current measurements are carried. Other parameters like electromagnetic radiation and magnetic fields could also be measured with the proper instruments and set-up. Creative assemblages with rocks and rocky materials have been proposed, like the usage of water to close the circuit between the rock prisms and electrodes (Balk *et al.* 2009), which allows to measure chemical redox occurring in the water itself following peroxy links migration; or the measurement of voltages generated by fault gouge under stresses, simulated with granular materials (Leeman *et al.* 2014). It is an experimental challenge, but trying to simulate conditions of pressure and temperature in depth of seismogenetic zones would bring rigor to the tests. Theoretical and experimental study, monitoring and compilations are necessary to draw relevant conclusions.

A simple way of discarding the internal electrical system of the Universal machine interfering with results is to have access to a completely hydraulic, pneumatic or mechanical machine. It is recommended to anyone interested in performing this kind of test to have access to a laboratory where setup can be left from day to day, due to its bulkiness and complexity to assemble. Good control of environmental EM noise and good functioning of electrical connections becomes necessary. Consulting a Geomechanical Standard (e.g. ASTM International Standard D5731-08) or any other paper regarding mechanical testing with rocks is also very important. Needless to say, having access to the best measuring instruments, cables and samples possible is very important. Also filters and amplifying circuits may be necessary.

Although mechanical processes related to EM phenomena have been and are currently studied in great detail, a stronger interdisciplinary work shall be required in order to advance further on in the matter. We consider that in order to clarify the existence (or non-existence) of Earthquake precursors and their dynamics, mutual work among scientific community is required. It is expected that unsupported skepticism regarding physical phenomena related to earthquakes (aside from the seismic wave itself) disappears. Only rigorous and objective studies may lead to the understanding of the wide range of reported electrical; magnetic; ionospheric; thermal; biological; (the list goes on) anomalies possibly related to natural seismic activity.

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