Fracture of piezoelectric materials causing electromagnetic emissions

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Out-line

- EM emissions and Earthquakes
- Experiments
- Piezoelectric formulation
    - Cauchy equations of motion
    - Maxwell's equations
    - Variational principle
- Preliminary results
- Conclusions and future work
- Publications

EM emissions & EQs

Initial report of ULF magnetic emissions associated with seismic activity

GEOPHYSICAL RESEARCH LETTERS, VOL. 17, NO. 9, PAGES 1465-1468, AUGUST 1990

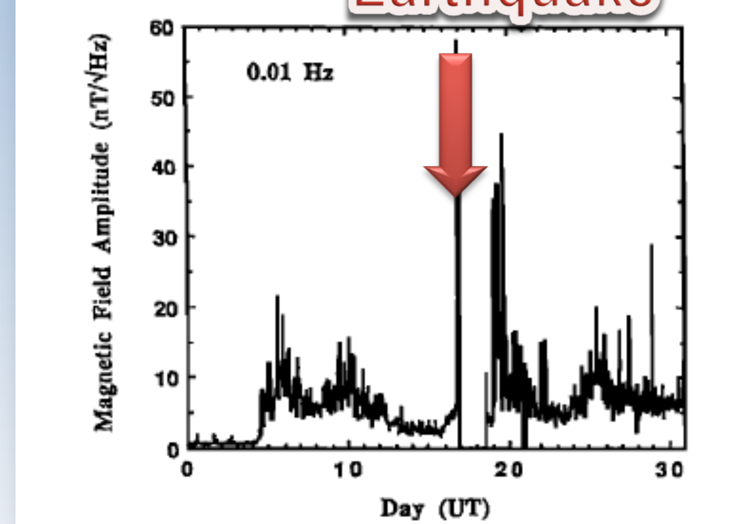
LOW-FREQUENCY MAGNETIC FIELD MEASUREMENTS NEAR THE EPICENTER OF THE M_S 7.1 LOMA PRIETA EARTHQUAKE

A. C. Fraser-Smith, A. Bernardi[1], P. R. McGill, M. E. Ladd, R. A. Helliwell, and O. G. Villard, Jr.

STAR Laboratory, Stanford University

ULF magnetic field measurements near (about 7 km) the epicenter of the imminent Loma Prieta earthquake have revealed anomalous activity almost two weeks before the earthquake with a remarkable increase three hours before.

Loma Prieta Earthquake



Experiments

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Physics and Chemistry of the Earth 31 (2006) 389–396

PHYSICS and CHEMISTRY of the EARTH
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Electric currents streaming out of stressed igneous rocks – A step towards understanding pre-earthquake low frequency EM emissions

Friedemann T. Freund [a,b,*], Akihiro Takeuchi [b,c], Bobby W.S. Lau [b]

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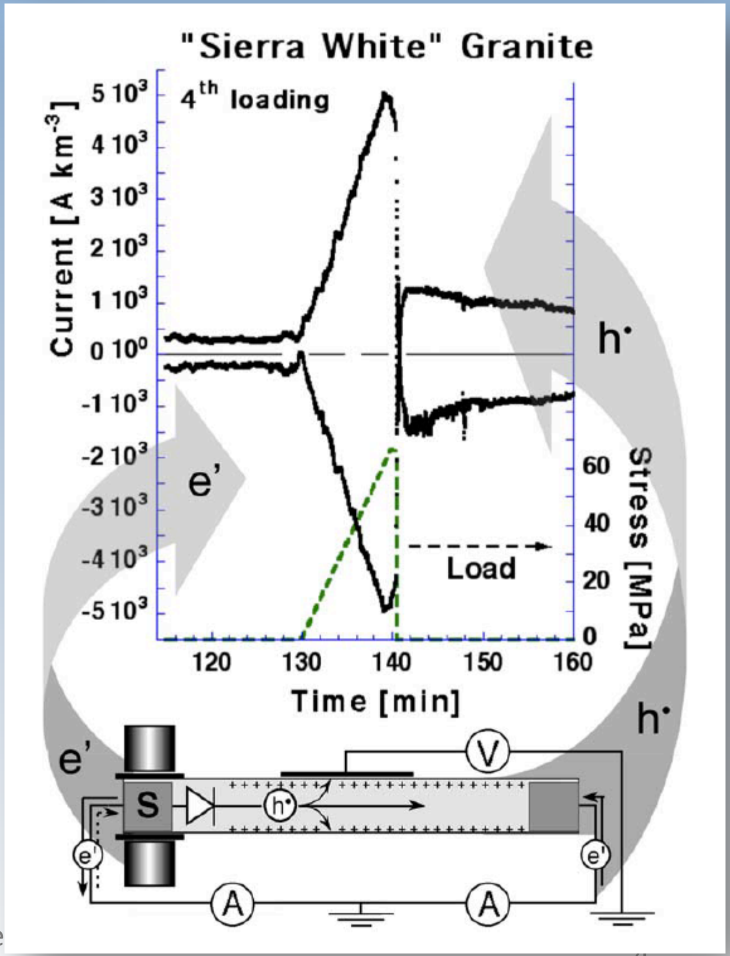
Accepted 6 February 2006
Available online 19 May 2006



These experiments possibly indicate a single mechanism responsible for the EM emissions. It is based on stress activated p-type charge carriers in igneous rocks creating a battery effect that successfully describes such emissions.

Experiments

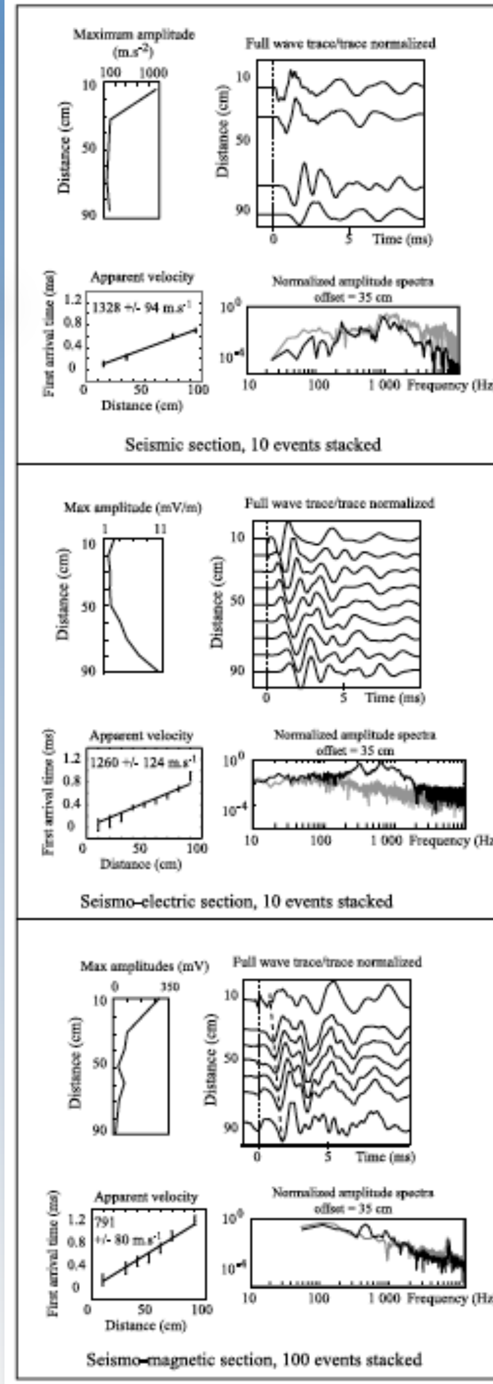
GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L01302, doi:10.1029/2005GL024582, 2006

First laboratory measurements of seismo-magnetic conversions in fluid-filled Fontainebleau sand

C. Bordes,[1] L. Jouniaux,[2] M. Dietrich,[1] J.-P. Pozzi,[3] and S. Garambois[1]

Received 7 September 2005; revised 29 October 2005; accepted 16 November 2005; published 6 January 2006.

"The first arrival times of seismo-electric and seismo-magnetic fields clearly indicate that these two fields are coupled to different propagation modes, an observation that is consistent with electrokinetic theory. Fast longitudinal modes generate only seismo-electric field whereas transverse modes are coupled to magnetic fields."



Experiments

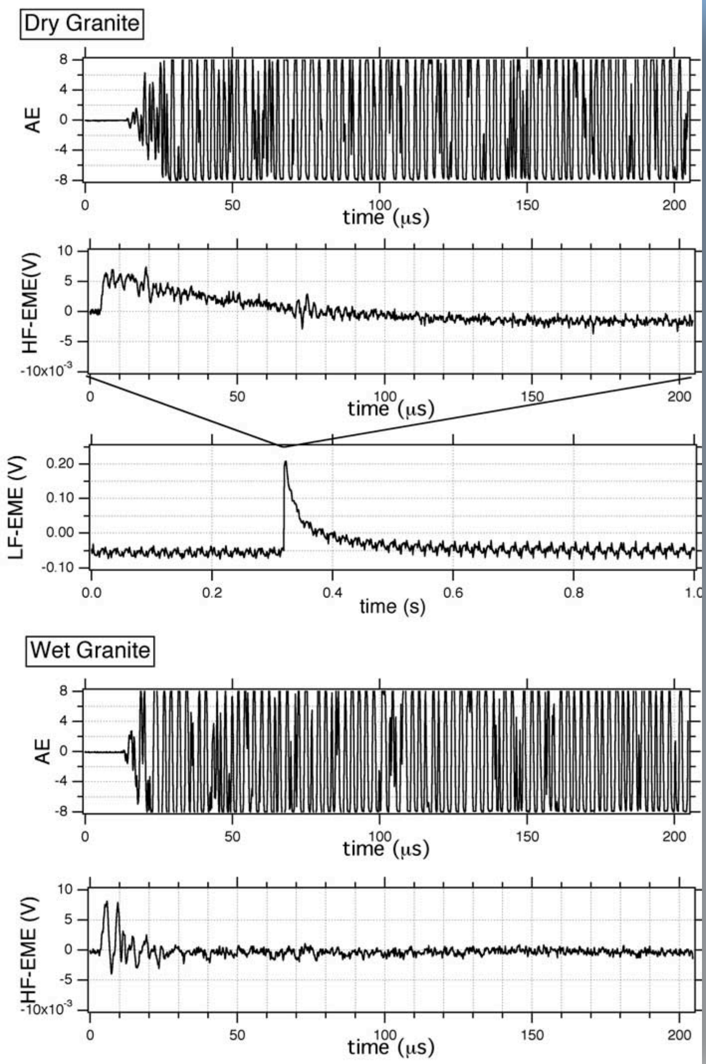
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, B09204, doi:10.1029/2004JB003092, 2004

Electromagnetic emissions from dry and wet granite associated with acoustic emissions

Shingo Yoshida[1] and Tsutomu Ogawa
Earthquake Research Institute, University of Tokyo, Tokyo, Japan

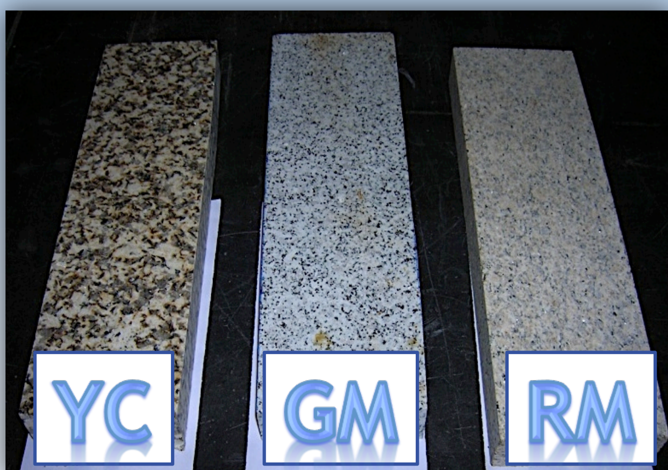
Received 17 March 2004; revised 11 June 2004; accepted 25 June 2004; published 11 September 2004.

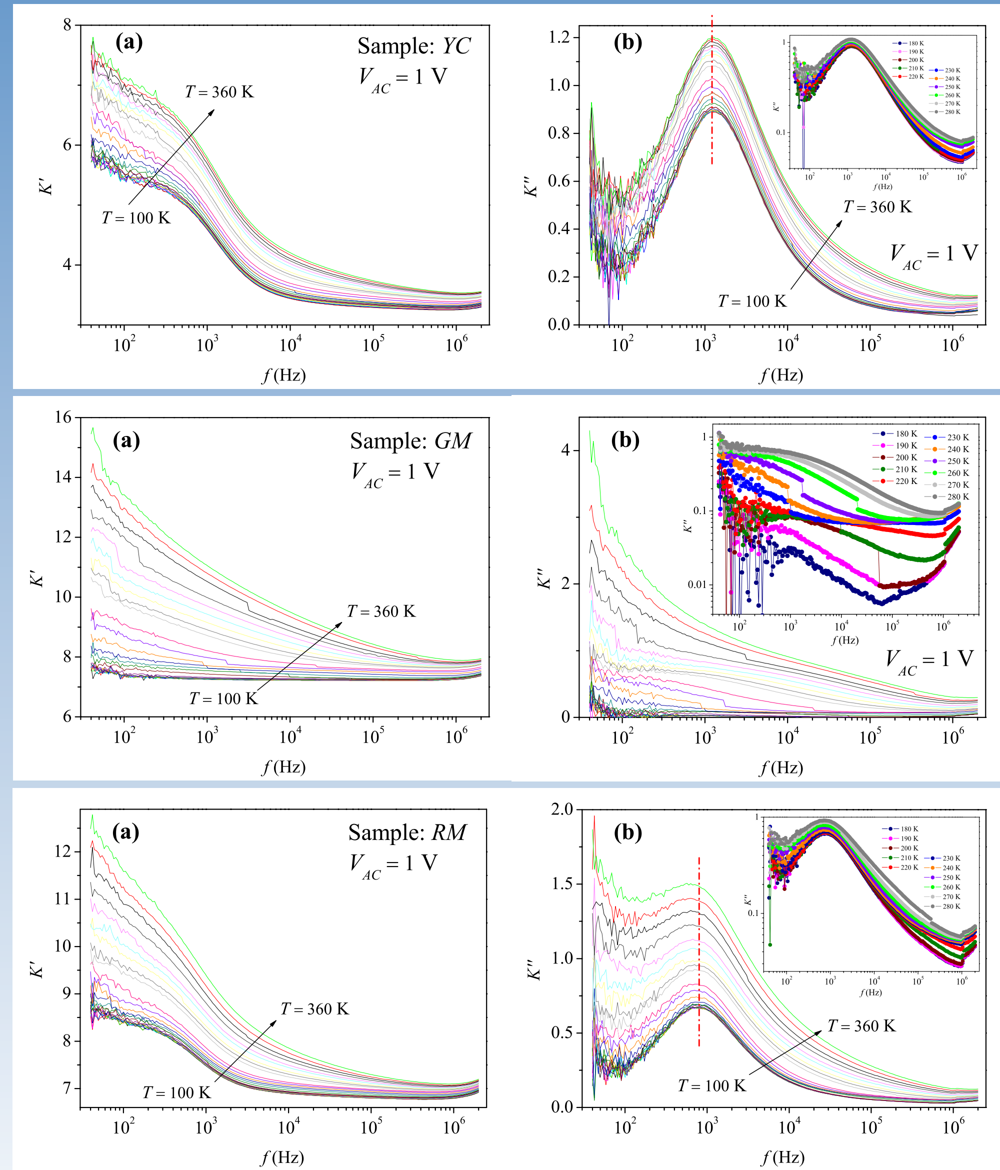
"In the wet rock experiments, EM emissions in the HF range were detected accompanied with AEs, although EMEs in the low-frequency range were not observed. In contrast, in the dry rock experiments, EMEs in both the high-frequency and low-frequency ranges were detected. The generation mechanism can be explained based on piezoelectricity and compensation charges."



Project

We are studying the electrical properties of different types of granitic samples in order to perform experiments involving *pressure stimulated electromagnetic emissions.*





a) Real part of the dielectric constant; b) Imaginary part of the dielectric constant.

Cauchy equations

- Mass conservation

$$\frac{\partial(J\rho)}{\partial t} = 0 \qquad \text{with} \qquad J = \det \boldsymbol{F}$$

- Cauchy equation of motion and Cauchy lemma

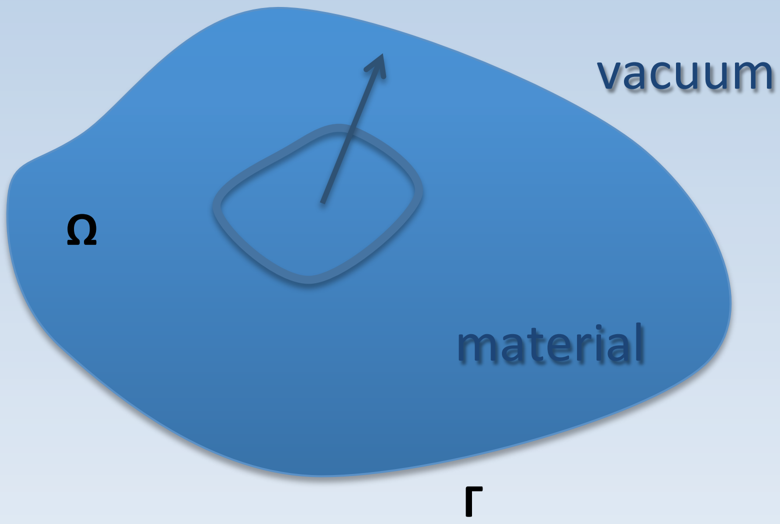
$$\nabla \cdot \boldsymbol{\sigma} = \rho \frac{\mathrm{D}\dot{\boldsymbol{u}}}{\mathrm{D}t}$$

$$\boldsymbol{n}^T \boldsymbol{\sigma} = \boldsymbol{t}$$

Maxwell equations

- Maxwell's equations for insulators $\rho_{free} = 0$ and $\boldsymbol{j}_{free} = \boldsymbol{0}$.

$$\begin{aligned} \nabla \times \boldsymbol{h} + \dot{\boldsymbol{d}} &= 0 \\ \nabla \cdot \boldsymbol{b} &= 0 \\ \nabla \times \boldsymbol{e} + \dot{\boldsymbol{b}} &= 0 \\ \nabla \cdot \boldsymbol{d} &= 0 \end{aligned}$$



With boundary conditions

$$\boldsymbol{n} \cdot [[\boldsymbol{b}]] = \boldsymbol{0} \qquad \boldsymbol{n} \times [[\boldsymbol{h} - \boldsymbol{v} \times \boldsymbol{d}]] = \boldsymbol{0}$$

$$\boldsymbol{n} \cdot [[\boldsymbol{d}]] = \boldsymbol{0} \qquad \boldsymbol{n} \times [[\boldsymbol{e} + \boldsymbol{v} \times \boldsymbol{b}]] = \boldsymbol{0}$$

Variational principle

- Strain tensor

$$\boldsymbol{\varepsilon} = \frac{1}{2}\left(\boldsymbol{b} - \boldsymbol{I}\right)$$

Ogdon model, N=2 *(Mooney-Rivlin material)*

- Total Helmoltz free energy

Derived to generate the correct expression for the Maxwell stress tensor

$$\overline{\psi}(\boldsymbol{\varepsilon}, \boldsymbol{d}, \boldsymbol{h}) = \frac{1}{2}(1-D)\,\boldsymbol{\varepsilon}^T : \mathcal{C} : \boldsymbol{\varepsilon} + \frac{1}{2}\mu \boldsymbol{h}^T(\boldsymbol{I} + 2\boldsymbol{\varepsilon})\boldsymbol{h} + \frac{1}{2\epsilon}\boldsymbol{d}^T(\boldsymbol{I} + 2\boldsymbol{\varepsilon})\boldsymbol{d} - \frac{1}{2}\left(\frac{1}{\epsilon}\boldsymbol{d}\cdot\boldsymbol{d} + \mu\boldsymbol{h}\cdot\boldsymbol{h}\right)\mathrm{tr}[\boldsymbol{\varepsilon}] + \boldsymbol{d}\cdot(\mathcal{I} : \boldsymbol{\varepsilon})$$

Deformation energy | Electromagnetic terms | Piezoelectric effect

Where *D* is the damage variable

Variational principle

- The corresponding damage loading function

$$\varphi(\boldsymbol{\varepsilon}) = (1 - D)\varepsilon_1 - \varepsilon_{\max}$$

- The following loading/unloading conditions

$$\varphi(\boldsymbol{\varepsilon}) \leq 0$$

$$\dot{D}\varphi(\boldsymbol{\varepsilon}) = 0$$

$$\dot{D} \geq 0$$

- The Kirchhoff stress tensor, the electric field and the magnetic induction

$$\boldsymbol{\tau} = \frac{\partial \overline{\psi}}{\partial \boldsymbol{\varepsilon}} \qquad \boldsymbol{e} = \frac{\partial \overline{\psi}}{\partial \boldsymbol{d}} \qquad \boldsymbol{b} = \frac{\partial \overline{\psi}}{\partial \boldsymbol{h}}$$

Variational principle

- The first variation of ***τ***, ***e*** and ***b*** with respect to ***ε***, ***d*** and ***h***

$$\delta\boldsymbol{\tau} = \frac{\partial^2\overline{\psi}}{\partial\boldsymbol{\varepsilon}^2} : \delta\boldsymbol{\varepsilon} + \frac{\partial^2\overline{\psi}}{\partial\boldsymbol{\varepsilon}\partial\boldsymbol{d}} \cdot \delta\boldsymbol{d} + \frac{\partial^2\overline{\psi}}{\partial\boldsymbol{\varepsilon}\partial\boldsymbol{h}} \cdot \delta\boldsymbol{h}$$

$$\delta\boldsymbol{e} = \frac{\partial^2\overline{\psi}}{\partial\boldsymbol{d}\partial\boldsymbol{\varepsilon}} : \delta\boldsymbol{\varepsilon} + \frac{\partial^2\overline{\psi}}{\partial\boldsymbol{d}^2} \cdot \delta\boldsymbol{d} + \frac{\partial^2\overline{\psi}}{\partial\boldsymbol{d}\partial\boldsymbol{h}} \cdot \delta\boldsymbol{h}$$

$$\delta\boldsymbol{b} = \frac{\partial^2\overline{\psi}}{\partial\boldsymbol{h}\partial\boldsymbol{\varepsilon}} : \delta\boldsymbol{\varepsilon} + \frac{\partial^2\overline{\psi}}{\partial\boldsymbol{h}\partial\boldsymbol{d}} \cdot \delta\boldsymbol{d} + \frac{\partial^2\overline{\psi}}{\partial\boldsymbol{h}^2} \cdot \delta\boldsymbol{h}$$

*The third derivatives with respect **ε**, **d** and **h** are also needed for* ***b***

Variational principle

- Integrating in Ω provides the virtual work

$$\delta W = \int_{\Omega_0} \boldsymbol{\tau} : \nabla \delta \boldsymbol{u} \, \mathrm{d}\Omega_0 + \int_{\Omega_0} \dot{\boldsymbol{b}} \cdot \delta \boldsymbol{h} \, \mathrm{d}\Omega_0 - \int_{\Omega_0} (\nabla \times \delta \boldsymbol{h}) \cdot \boldsymbol{e} \, \mathrm{d}\Omega_0 + \int_{\Omega_0} \left(\nabla \times \boldsymbol{h} - \dot{\boldsymbol{d}} \right) \cdot \delta \boldsymbol{d} \, \mathrm{d}\Omega_0 +$$
$$r_b \int_{\Omega_0} \nabla \cdot \boldsymbol{b} \nabla \cdot \delta \boldsymbol{b} \mathrm{d}\Omega_0 + r_d \int_{\Omega_0} \nabla \cdot \boldsymbol{d} \nabla \cdot \delta \boldsymbol{d} \mathrm{d}\Omega_0 + \int_{\Gamma} \delta \lambda_b^I \boldsymbol{n} \cdot [[\boldsymbol{b}]] \mathrm{d}\Gamma + \int_{\Gamma} \delta \lambda_d^I \boldsymbol{n} \cdot [[\boldsymbol{d}]] \mathrm{d}\Gamma +$$
$$\int_{\Gamma} \delta \lambda_d^{II} \boldsymbol{n} \times [[\boldsymbol{h} - \boldsymbol{v} \times \boldsymbol{d}]] \mathrm{d}\Gamma + \int_{\Gamma} \delta \lambda_b^{II} \boldsymbol{n} \times [[\boldsymbol{e} + \boldsymbol{v} \times \boldsymbol{b}]] \mathrm{d}\Gamma - \int_{\Gamma_t} \boldsymbol{t} \cdot \delta \boldsymbol{u} \mathrm{d}\Gamma_t + \int_{\Gamma} \boldsymbol{e} \times \delta \boldsymbol{h} \, \mathrm{d}\Gamma = 0$$

The second variation of W is also required for the application of Newton's method.

- The backward-Euler method is used for the integration

$$\dot{\boldsymbol{b}} \cong \frac{\boldsymbol{b}_{n+1} - \boldsymbol{b}_n}{\Delta t}$$

$$\dot{\boldsymbol{d}} \cong \frac{\boldsymbol{d}_{n+1} - \boldsymbol{d}_n}{\Delta t}$$

Variational principle

- The δ-variation of ∇(•)

$$\delta\nabla\left(\bullet\right)=\nabla\delta\left(\bullet\right)-\nabla\left(\bullet\right)\nabla\delta\boldsymbol{u}$$

- The d-variation of ∇(•)

Here • is a tensor and
∇ is a spatial gradient

$$\mathrm{d}\nabla\left(\bullet\right)=\nabla\mathrm{d}\left(\bullet\right)-\nabla\left(\bullet\right)\nabla\mathrm{d}\boldsymbol{u}$$

- The 2D discretization is based on a 3-node triangle

$$\boldsymbol{u}=\sum N_K\boldsymbol{u}_K$$

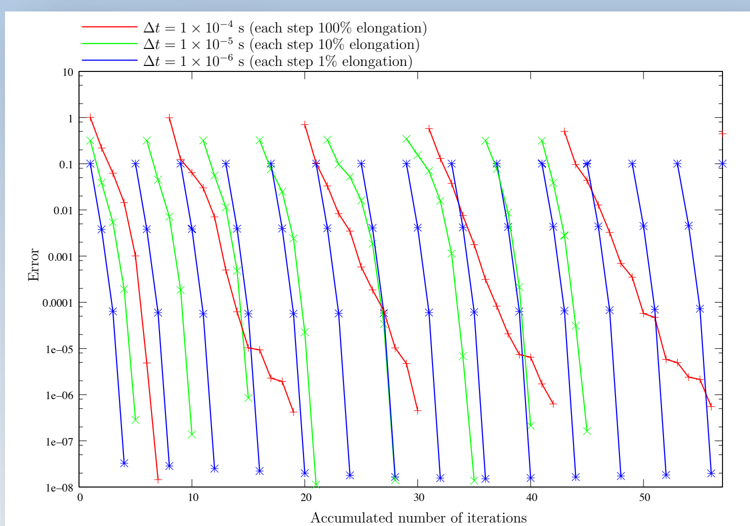
$$\boldsymbol{d}=\sum N_K\boldsymbol{d}_K$$

$$h_z=\sum N_K(h_z)_K$$

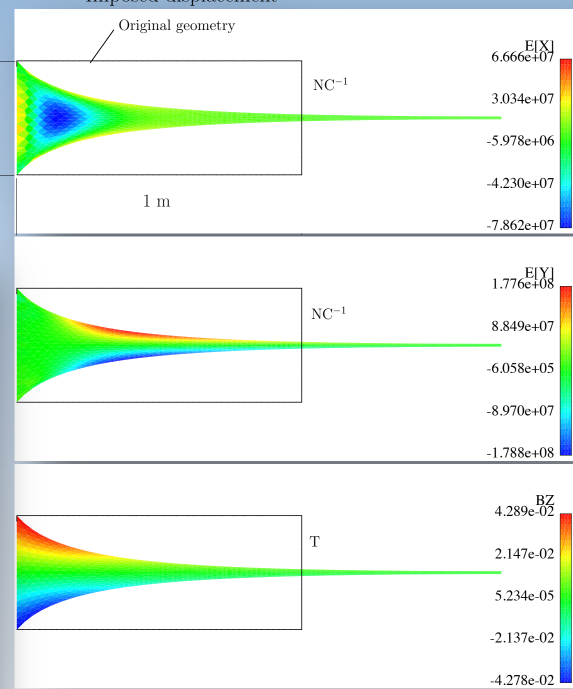
We use AceGen for the derivation of the discretized equations

Preliminary results

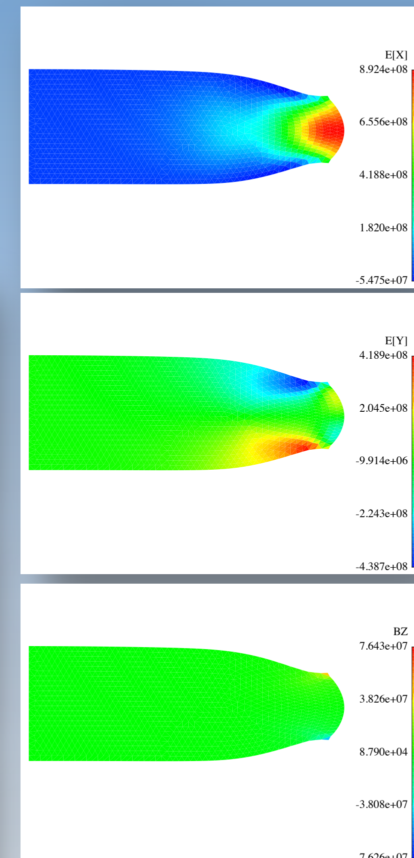
$$E = 69.59 \text{ GPa}$$
$$\nu = 0.357$$
$$\mu = 1.256 \times 10^{-6} \text{ Hm}^{-1}$$
$$\epsilon = 6 \times 10^{-9} \text{ Fm}^{-1}$$
$$\mathscr{I}_{11} = 15.08 \text{ Cm}^{-2}$$
$$\mathscr{I}_{12} = -5.207 \text{ Cm}^{-2}$$
$$\mathscr{I}_{23} = 12.71 \text{ Cm}^{-2}$$
$$\dot{u} = 1 \text{ ms}^{-1}$$



Imposed displacement

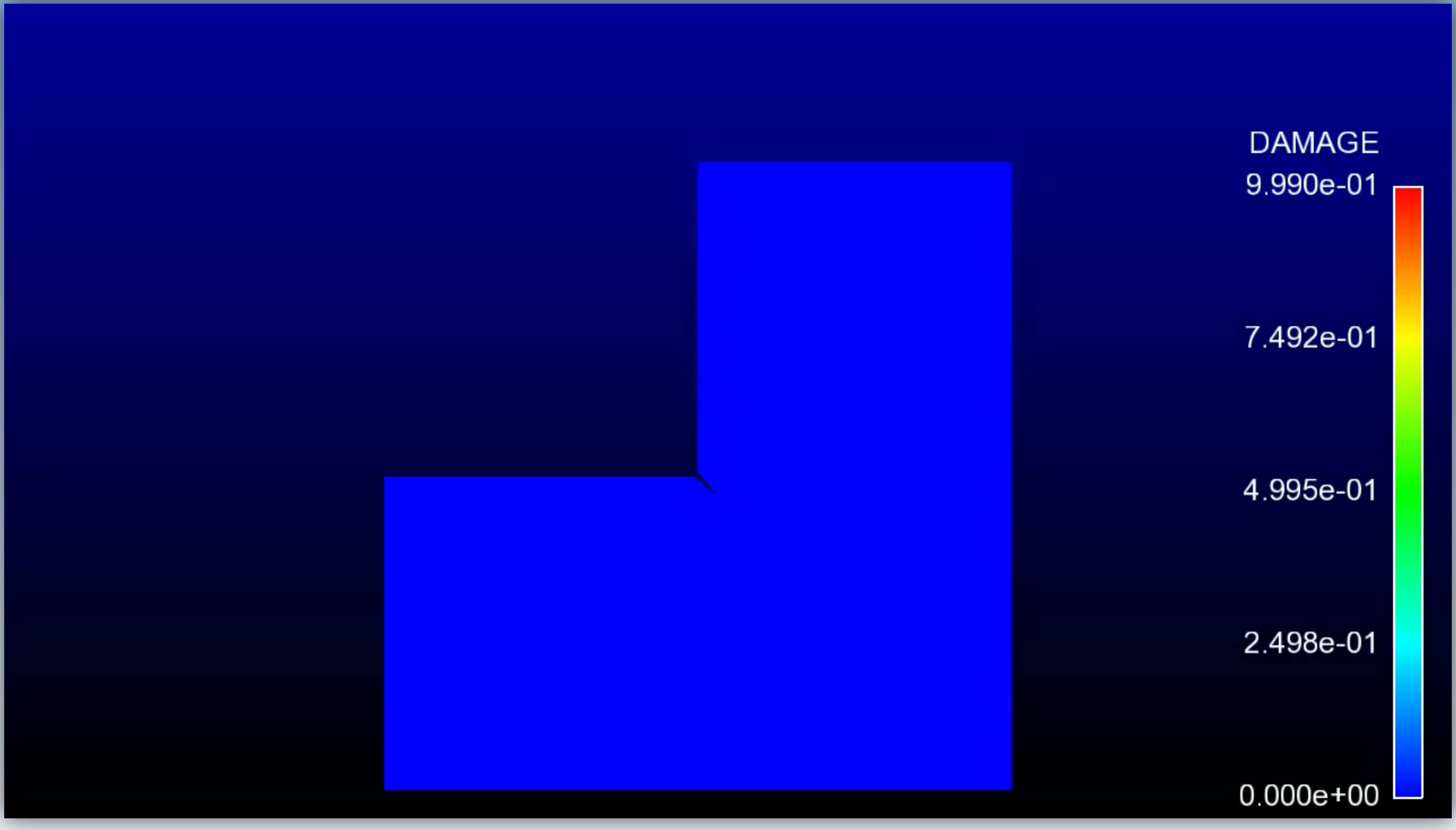


Imposed d_{xx}



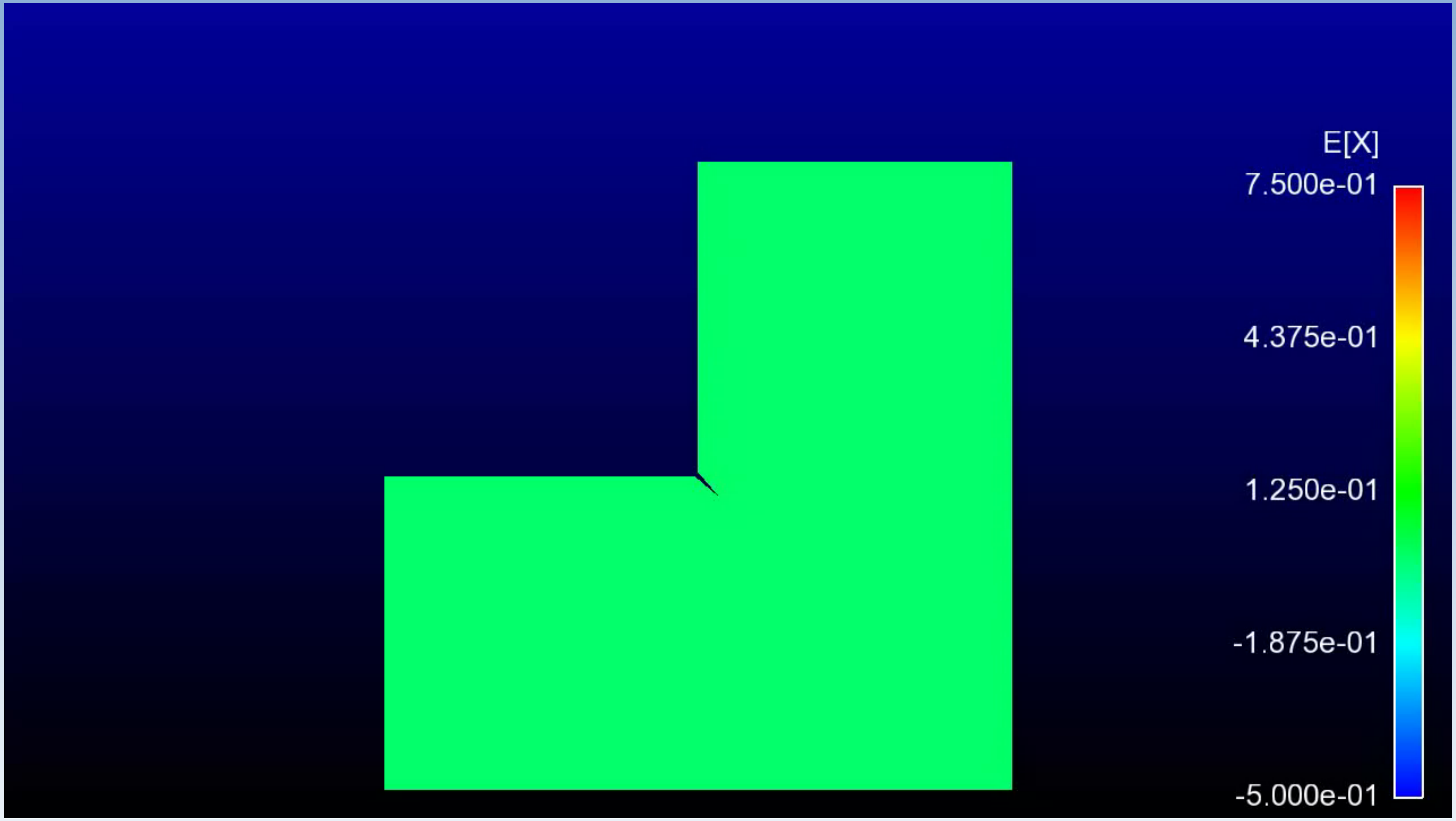
Preliminary results

Damage:



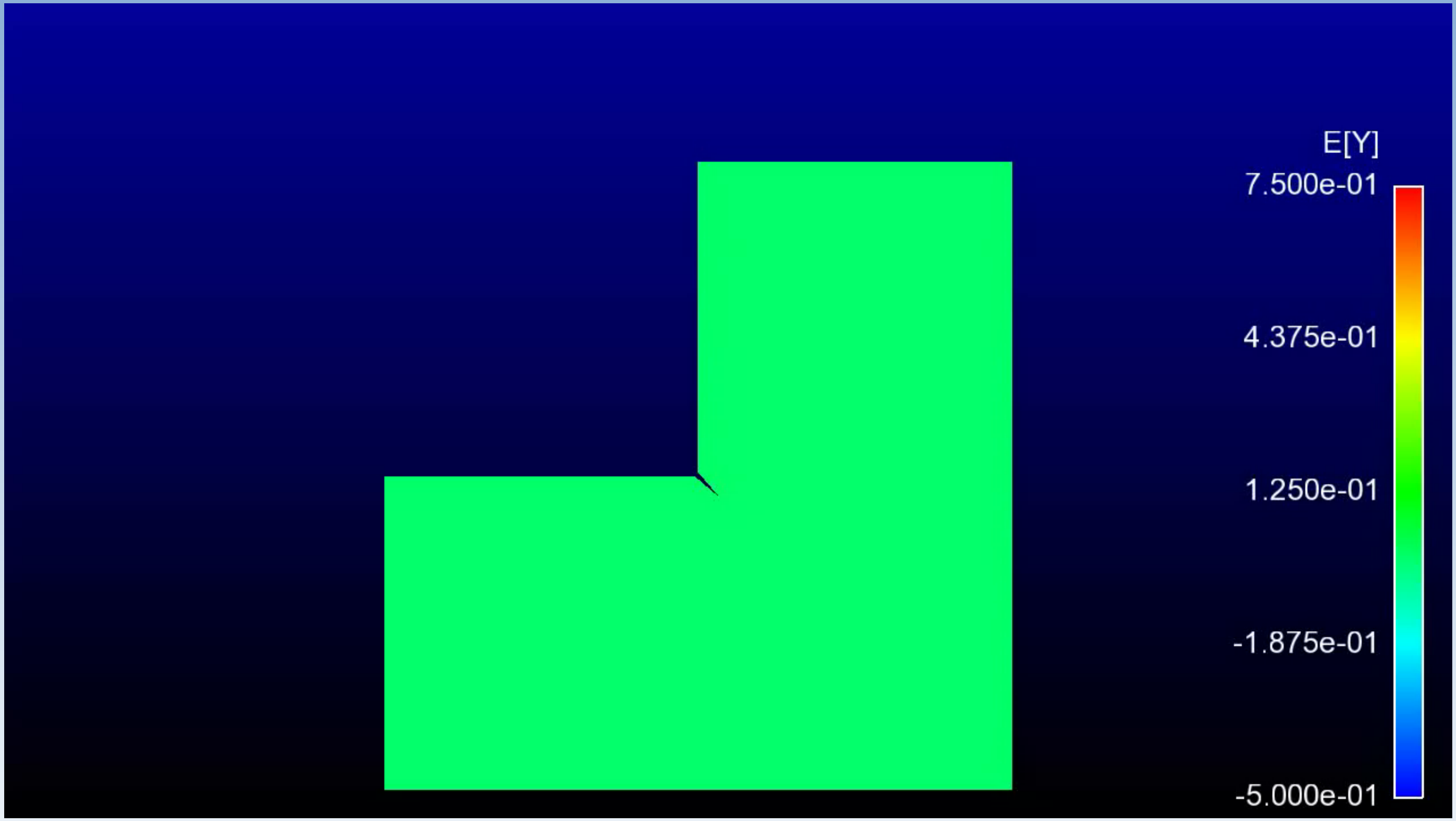
Preliminary results

E_x (V/m):



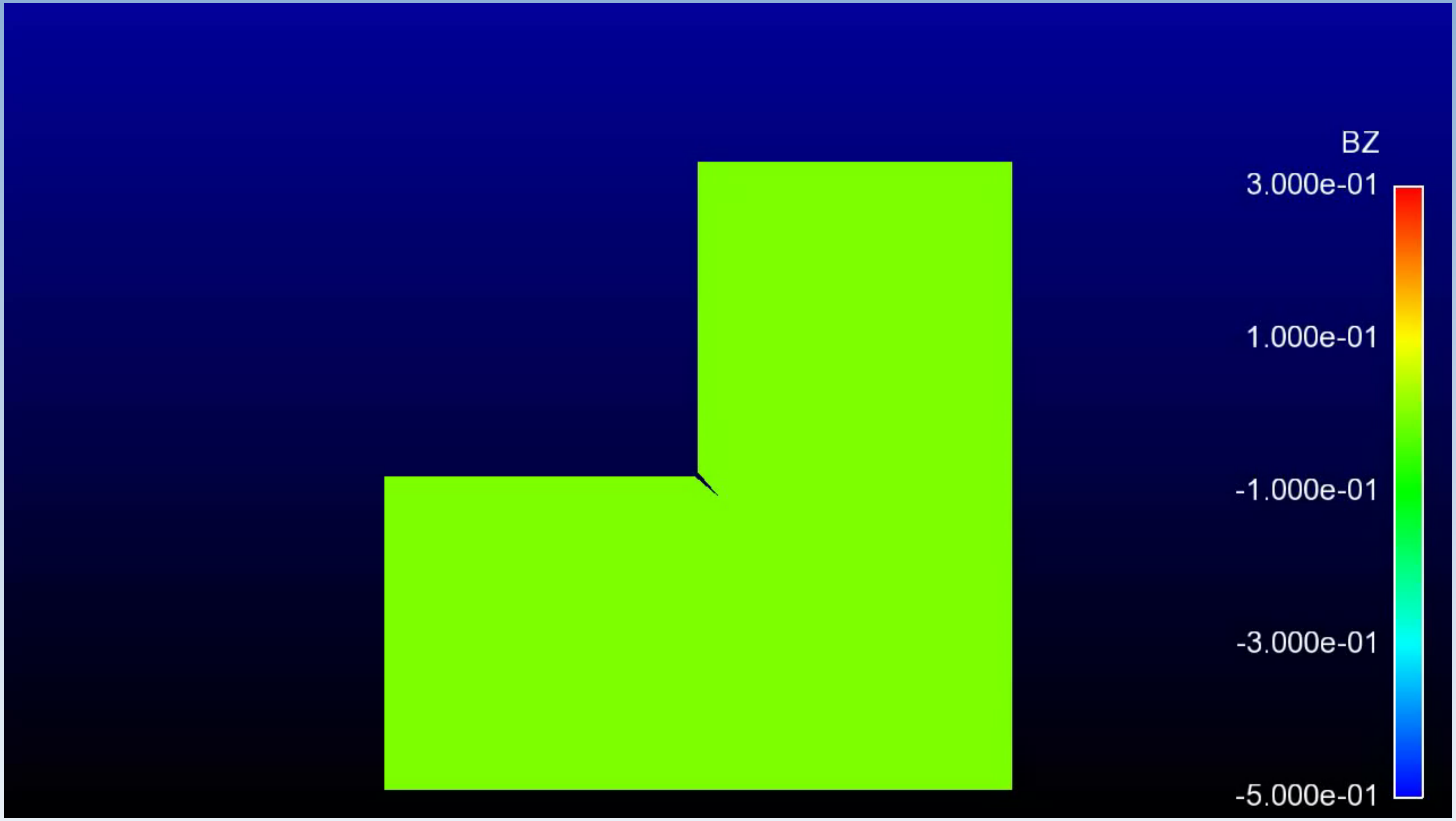
Preliminary results

E_y (V/m):



Preliminary results

B_z (T):



Conclusions and Future

- We were able to successfully integrate Cauchy equations of motion and Maxwell equations within a finite strain fracture framework

- Despite oscillations in the magnetic field, we found results physically significant and in agreement with what is expected

- Further *verification* and *validation* are required to firmly pursue additions to our approach

- Revision of the boundary conditions and inclusion of anisotropies are *natural developments* in the theory.

Publications

1. *Seismo-electromagnetic phenomena in the western part of the Eurasia-Nubia plate boundary*, H.G. Silva, M. Bezzeghoud, J.P. Rocha, P.F. Biagi, M. Tlemçani, R.N. Rosa, M.A. Salgueiro da Silva, J.F. Borges, B. Caldeira, A.H. Reis, and M. Manso, Nat. Hazards Earth Syst. Sci. 11, 241 (2011).

2. *The European VLF/LF radio network to search for earthquake precursors: setting up and natural/man-made disturbances*, P. F. Biagi, T. Maggipinto, F. Righetti, D. Loiacono, L. Schiavulli, T. Ligonzo, A. Ermini, I. A. Moldovan, A. S. Moldovan, A. Buyuksarac, H.G. Silva, M. Bezzeghoud, and M. E. Contadakis, Nat. Hazards Earth Syst. Sci. 11, 333 (2011).

3. *Atmospheric electrical field anomalies associated with seismic activity*, H.G. Silva, M. Bezzeghoud, A.H. Reis, R.N. Rosa, M. Tlemçani, J.F. Borges, B. Caldeira, and P.F. Biagi, Nat. Hazards Earth Syst. Sci. 11, 987 (2011).

4. *Wavelet analysis of the LF radio signals collected by the European VLF/LF network from July 2009 until April 2011*, F. Righetti, P. F. Biagi, T. Maggipinto, L. Schiavulli, T. Ligonzo, A. Ermini, I. A. Moldovan, A. S. Moldovan, A. Buyuksarac, H.G. Silva, M. Bezzeghoud, M. E. Contadakis, D.N. Arabelos and T.D. Xenos (submitted to Annals of Geophysics).

5. *Impedance properties of granitic rocks*, H.G. Silva, M.P.F. Graça, J. H. Monteiro, P. Moita, M. Tlemçani, R.N. Rosa, M. Bezzeghoud, S. K. Mendiratta (in preparation).

6. *Influence of seismic activity in the atmospheric electrical potential gradient in Lisbon (Portugal) from 1961 until 1991*, H.G. Silva, C. Serrano, M.M. Oliveira, M. Bezzeghoud, A.H. Reis, R.N. Rosa, and P.F. Biagi (in preparation).

7. *Piezoelectric effect during solid fracture causing electromagnetic emissions*, H.G. Silva, P.M. Areias, J.E. Garção, N. Van Goethem, and M. Bezzeghoud (in preparation).

Acknowledgements

Team

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CGE

Support

ESTÍMULO À CRIATIVIDADE E À QUALIDADE NA ACTIVIDADE DE INVESTIGAÇÃO
PROGRAMA DE ESTÍMULO À INVESTIGAÇÃO 2010
FUNDAÇÃO CALOUSTE GULBENKIAN
Serviço de Ciência
Prazo para a entrega das candidaturas: 24 de Setembro de 2010
FUNDAÇÃO CALOUSTE GULBENKIAN

QREN
QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
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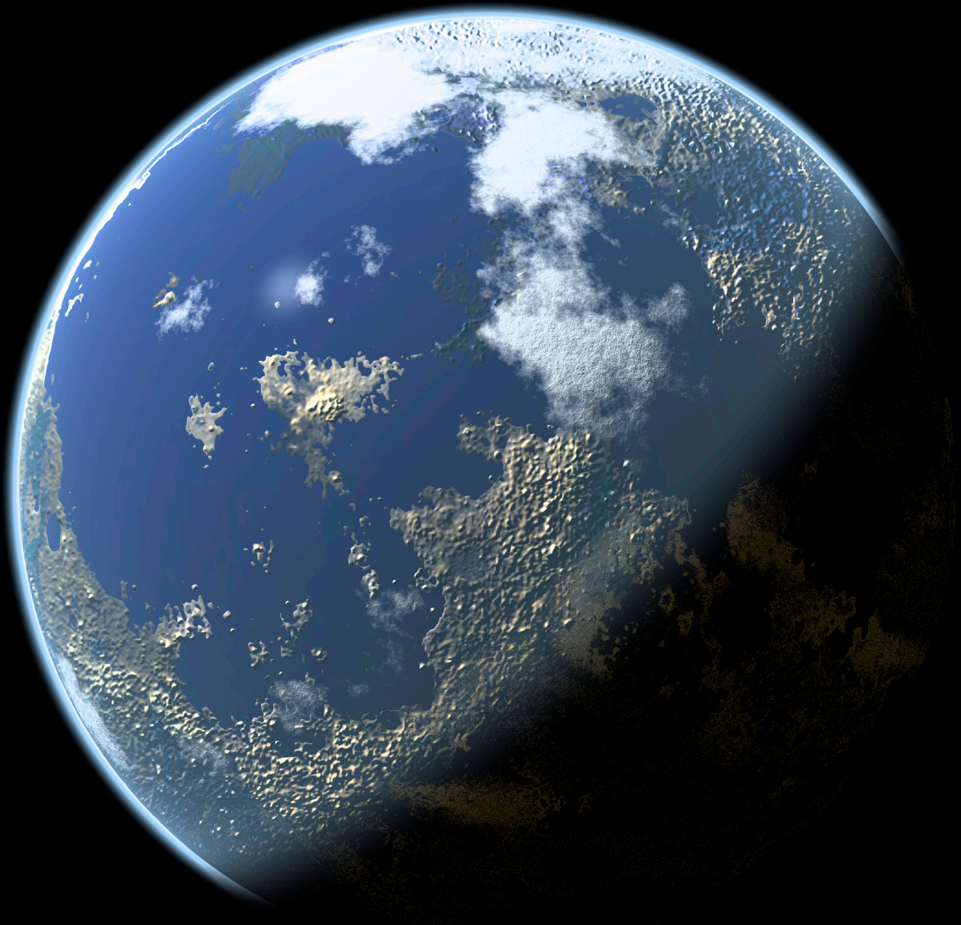

Thank you very much
for your attention!