# Numerical modeling of the coupled seismoelectric wave propagation in frequency domain

A. Budiman, M. Gharibi, C. Frenette, Aqsha,
R. Stewart, and L. Bentley

CREWES

UNIVERSITY OF CALGARY

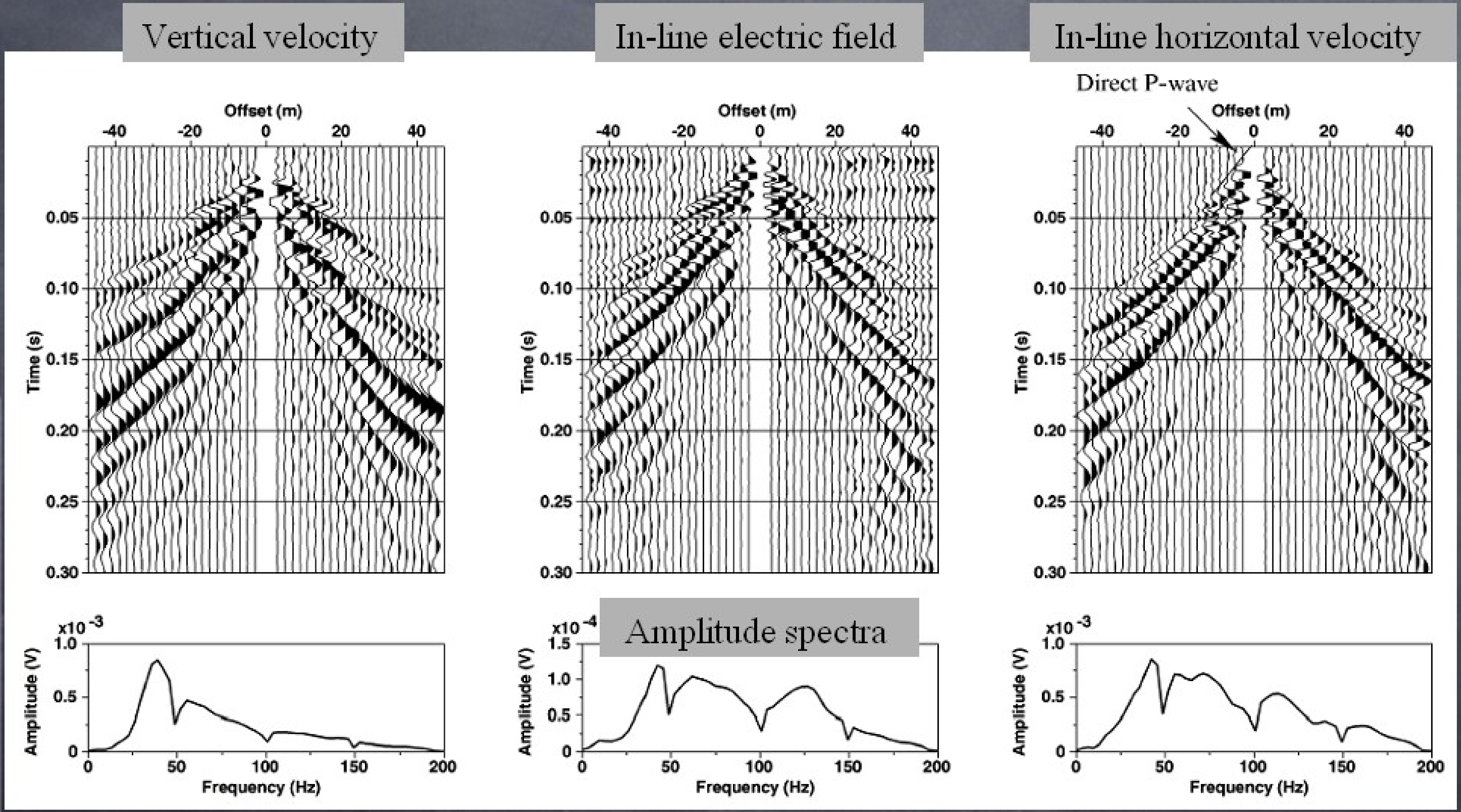
# Outline

- Introduction & motivation
- Maxwell's equations
- Simulation setup
- Results
- Future work

# Introduction

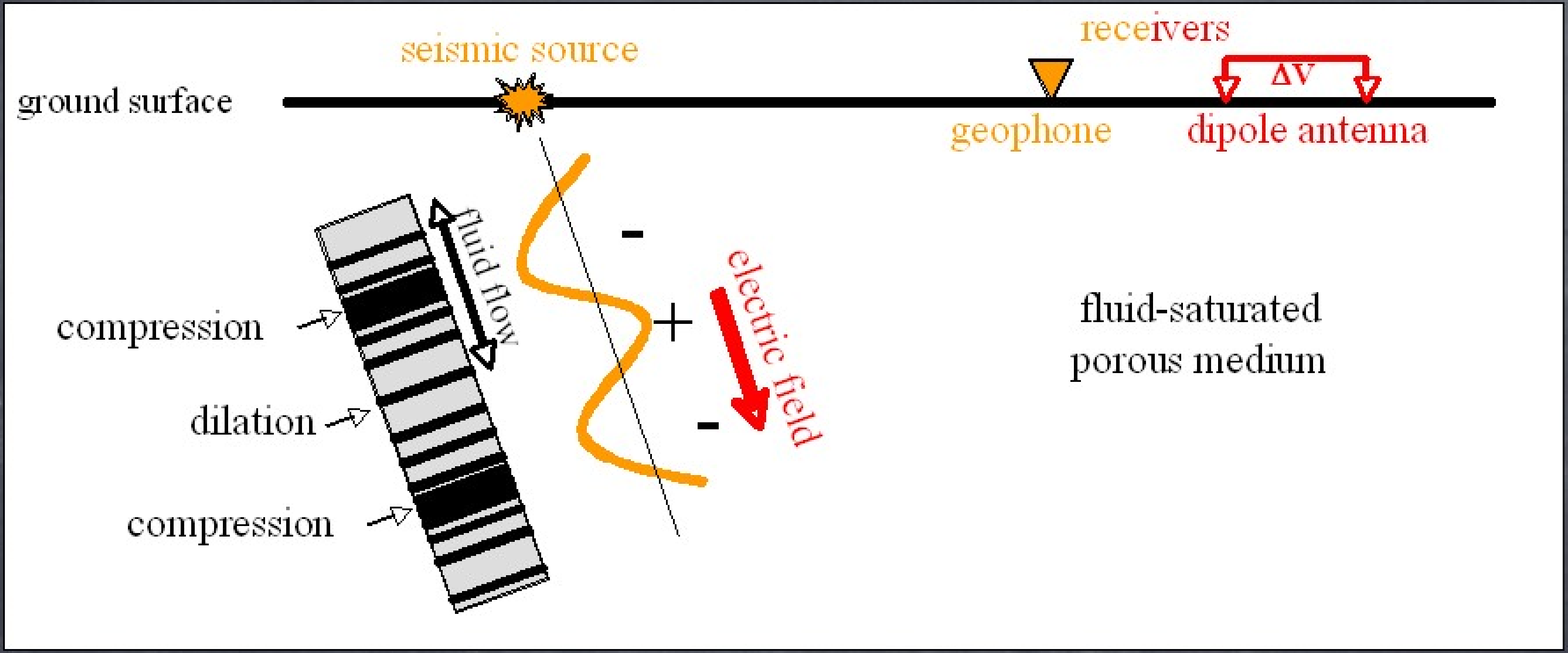
- Seismic waves can generate electromagnetic waves
- It has been observed since 1930s
- Renewed interest since 1990s with recent theoretical developments

# Data example

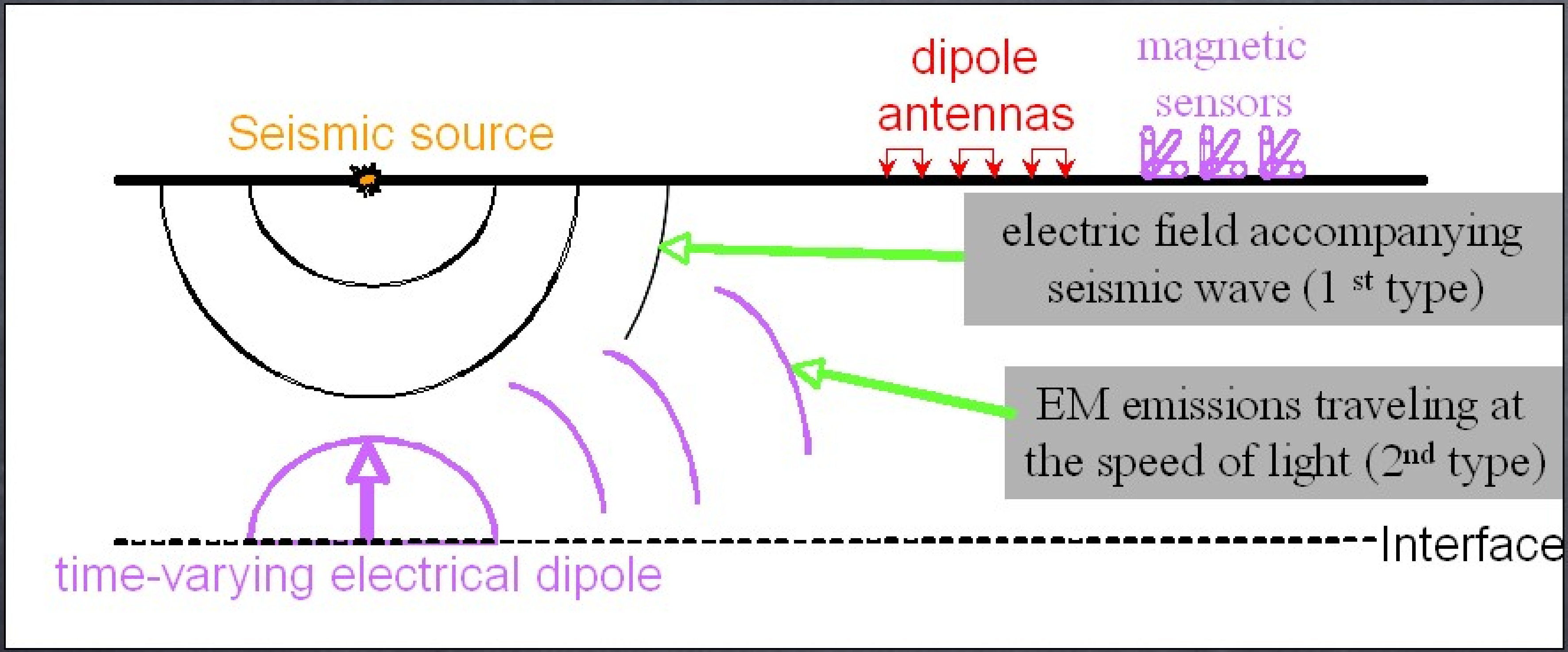



Source: Garambois & Dietrich (2001)

# Conceptual model

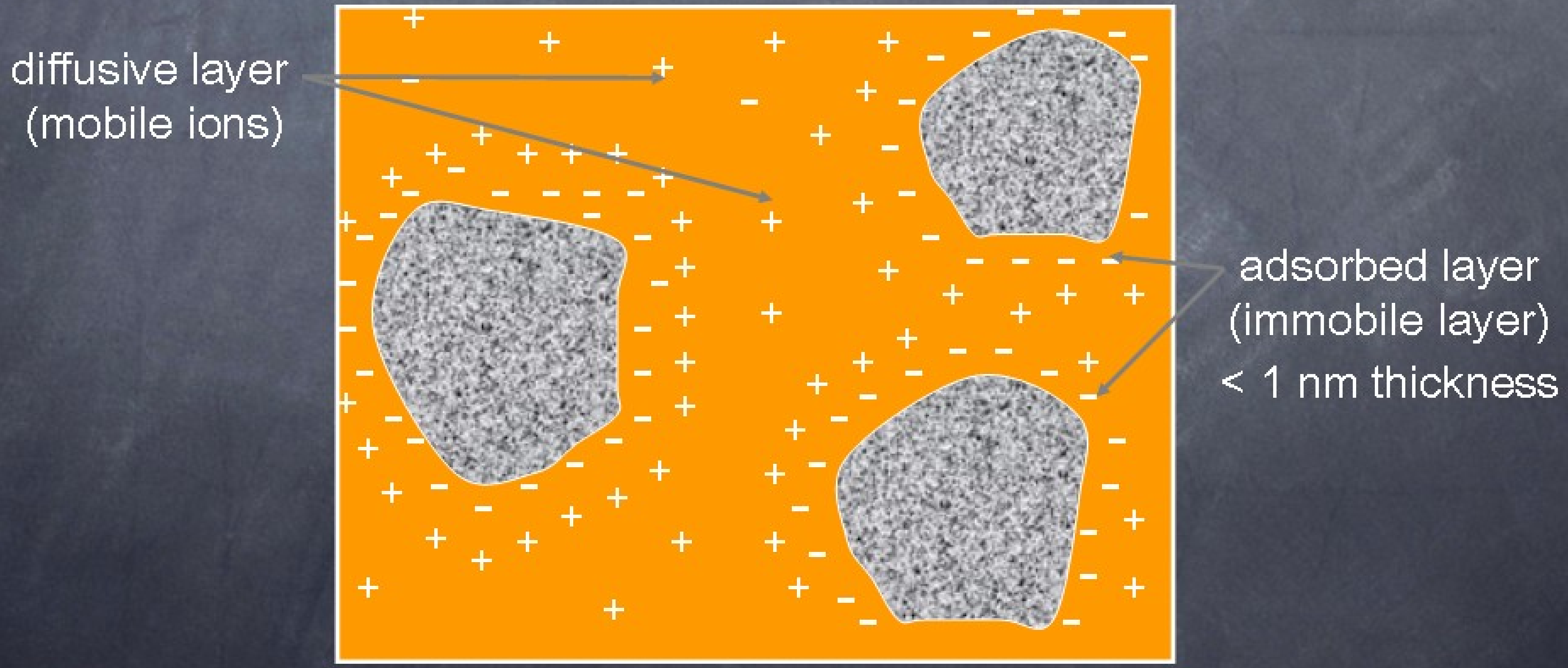


# Interface signal



# Electrical double layer

Electrical double layer in porous medium at the grain scale



# Motivation

- Electromagnetic wave production depends on relative motion between fluid and solid in porous media
- Properties like porosity are accessible from seismoelectric signal

# Insulating solid phase

$$\begin{aligned} \nabla \cdot \mathbf{B}_s &= 0 \\ \nabla \cdot \mathbf{D}_s &= 0 \\ \nabla \times \mathbf{E}_s &= -\frac{\partial \mathbf{B}_s}{\partial t} \\ \nabla \times \mathbf{H}_s &= \frac{\partial \mathbf{D}_s}{\partial t} \end{aligned}$$

# Conducting fluid phase

$$
\begin{aligned}
\nabla \cdot \mathbf{B}_f &= 0 \\
\nabla \cdot \mathbf{D}_f &= \sum_l e z_l N_l \\
\nabla \times \mathbf{E}_f &= -\frac{\partial \mathbf{B}_f}{\partial t} \\
\nabla \times \mathbf{H}_f &= \frac{\partial \mathbf{D}_f}{\partial t} + \sum_l e z_l \left[ -kTb_l \nabla N_l + e z_l b_l N_l \mathbf{E}_f + N_l \frac{\partial \mathbf{u}_f}{\partial t} \right]
\end{aligned}
$$

# Linear analysis

- Constitutive equations:

$$\mathbf{B}_\xi = \mu_0 \mathbf{H}_\xi \qquad \mathbf{D}_\xi = \epsilon_0 \kappa_\xi \mathbf{E}_\xi$$

- Field variables are sinusoidal

- Basic unperturbed solution is exponential decay of electrostatic potential with the characteristic (Debye) length:

$$\frac{1}{d^2} = \sum_l \frac{(ez_l)^2 N_l}{\epsilon_0 \kappa_f kT}$$

# F = ma

- Ionic conduction connected to elastic displacements by force balance:

$$
\begin{aligned}
-i\omega\rho_f \frac{\partial \mathbf{u}_f}{\partial t} &= \nabla \cdot \tau_f + \sum_l e z_l \left( N_l^0 \mathbf{e}_f + n_l \mathbf{E}_f^0 \right) \\
-i\omega\rho_s \frac{\partial \mathbf{u}_s}{\partial t} &= \nabla \cdot \tau_s
\end{aligned}
$$

- Fluid stress state includes viscosity

# Macroscopic field

- Porosity determines signal strength
- Four sources of current density

$$\nabla \cdot \overline{\mathbf{D}} = \phi \sum_l e z_l \overline{n}_l,$$

$$\nabla \cdot \overline{\mathbf{B}} = 0,$$

$$\nabla \times \overline{\mathbf{E}} = i\omega \overline{\mathbf{B}},$$

$$\nabla \times \overline{\mathbf{H}} = -i\omega \overline{\mathbf{D}} + \phi(\overline{\mathbf{J}}_d + \overline{\mathbf{J}}_s + \overline{\mathbf{J}}_n + \overline{\mathbf{J}}_c)$$

# Current density

- Diffusion current driven by gradient of averaged ionic density
- Conduction (electronic) current driven by electric field
- Streaming current due to ionic motion from elastic displacement
- Excess ions migrating in and out of interfaces

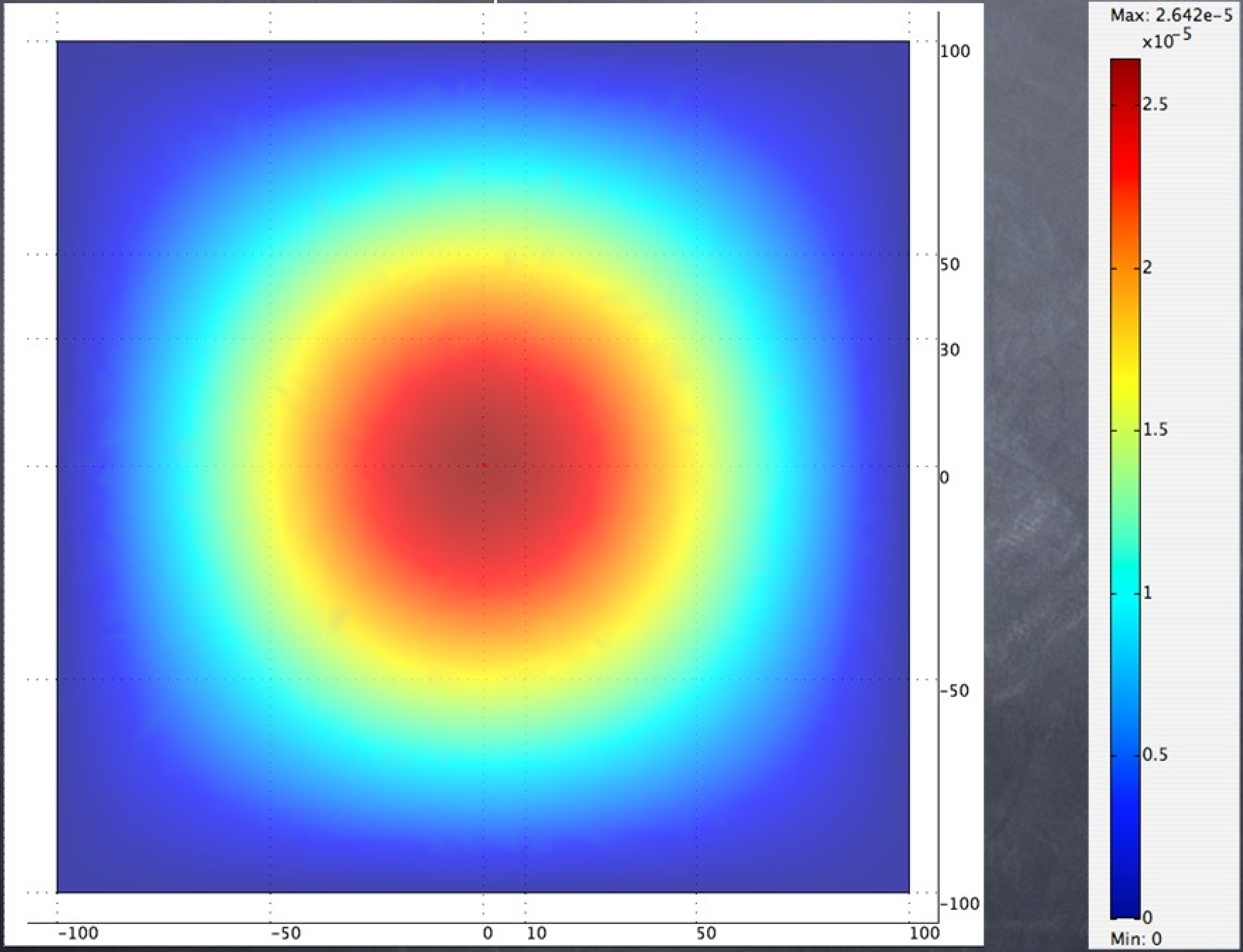
# Simulation setup

- Using FEMLAB to solve 3 coupled vector fields: electric field, solid displacement, relative solid-liquid displacement
- 3 coupled PDEs for the 3 fields
- 200 m x 200 m x 200 m solid
- 10 MN sharp Gaussian pulse on top surface
- Elastic displacement decays sufficiently

# Important parameters

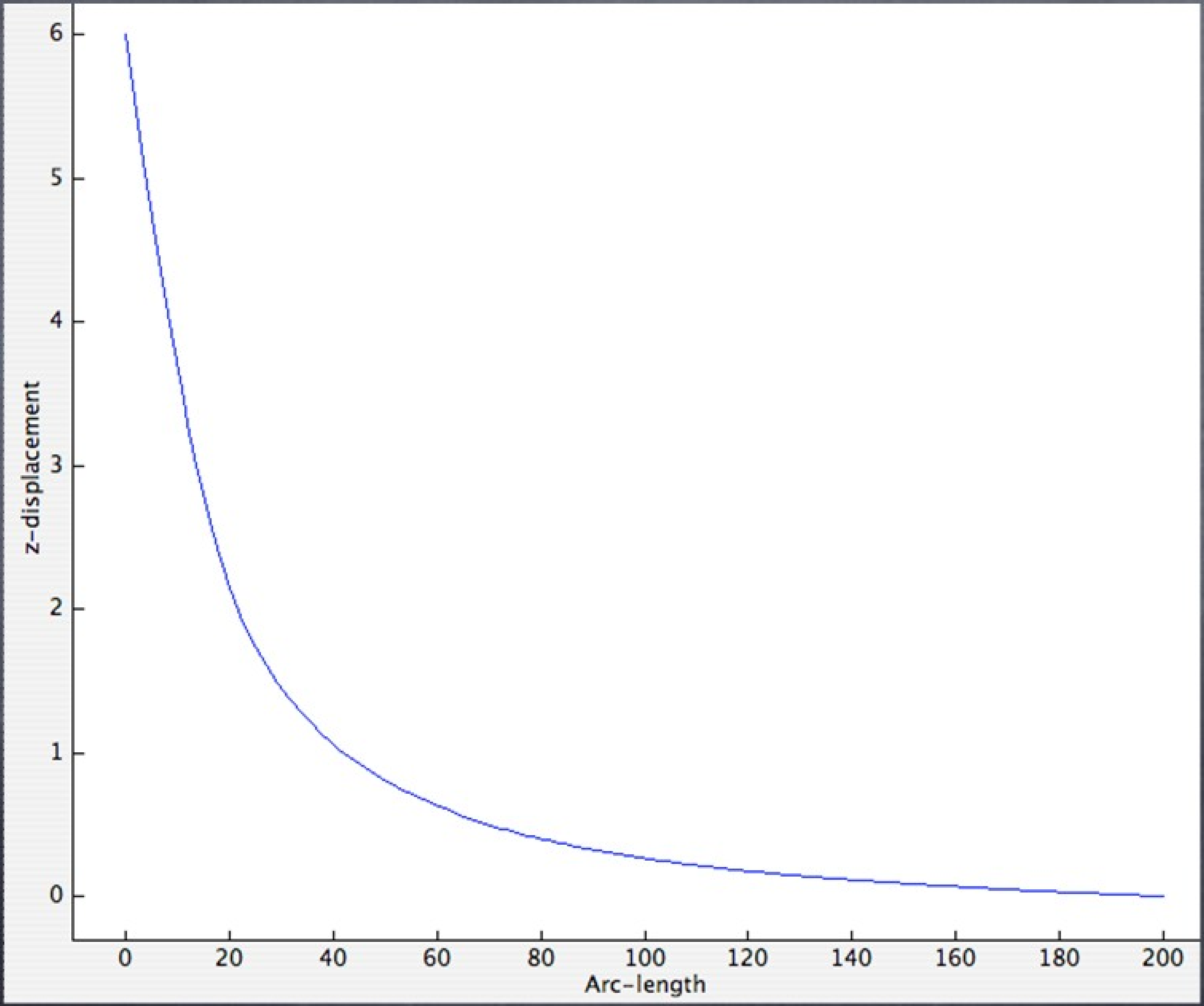
- Porosity = 0.20
- Conductivity = 9.3E-4 hmo/m
- Density = 1000 kg/m3
- Viscosity = 0.01 poise

# Vertical elastic displacement



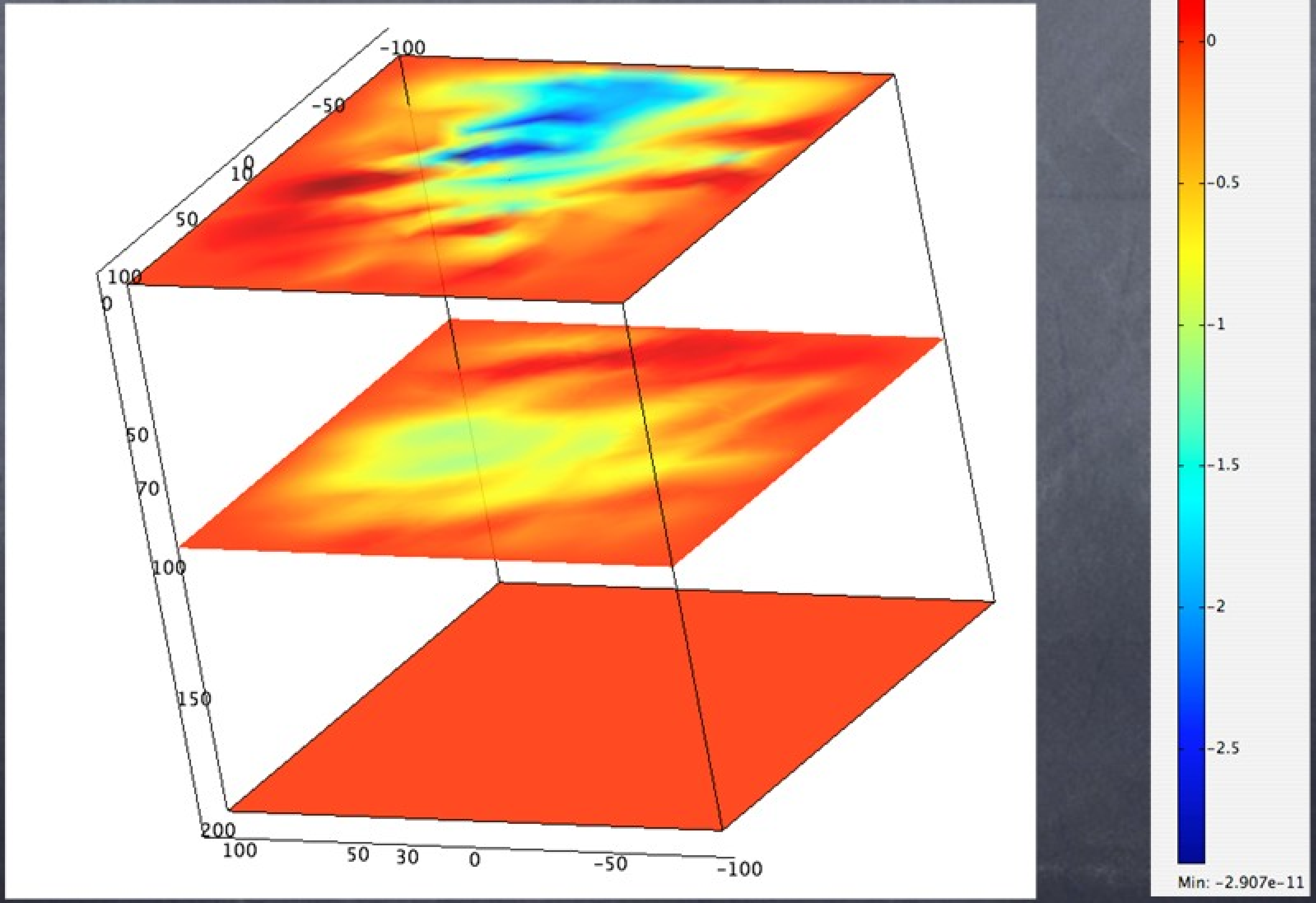
# Vertical elastic displacement profile

x $10^{-4}$ m

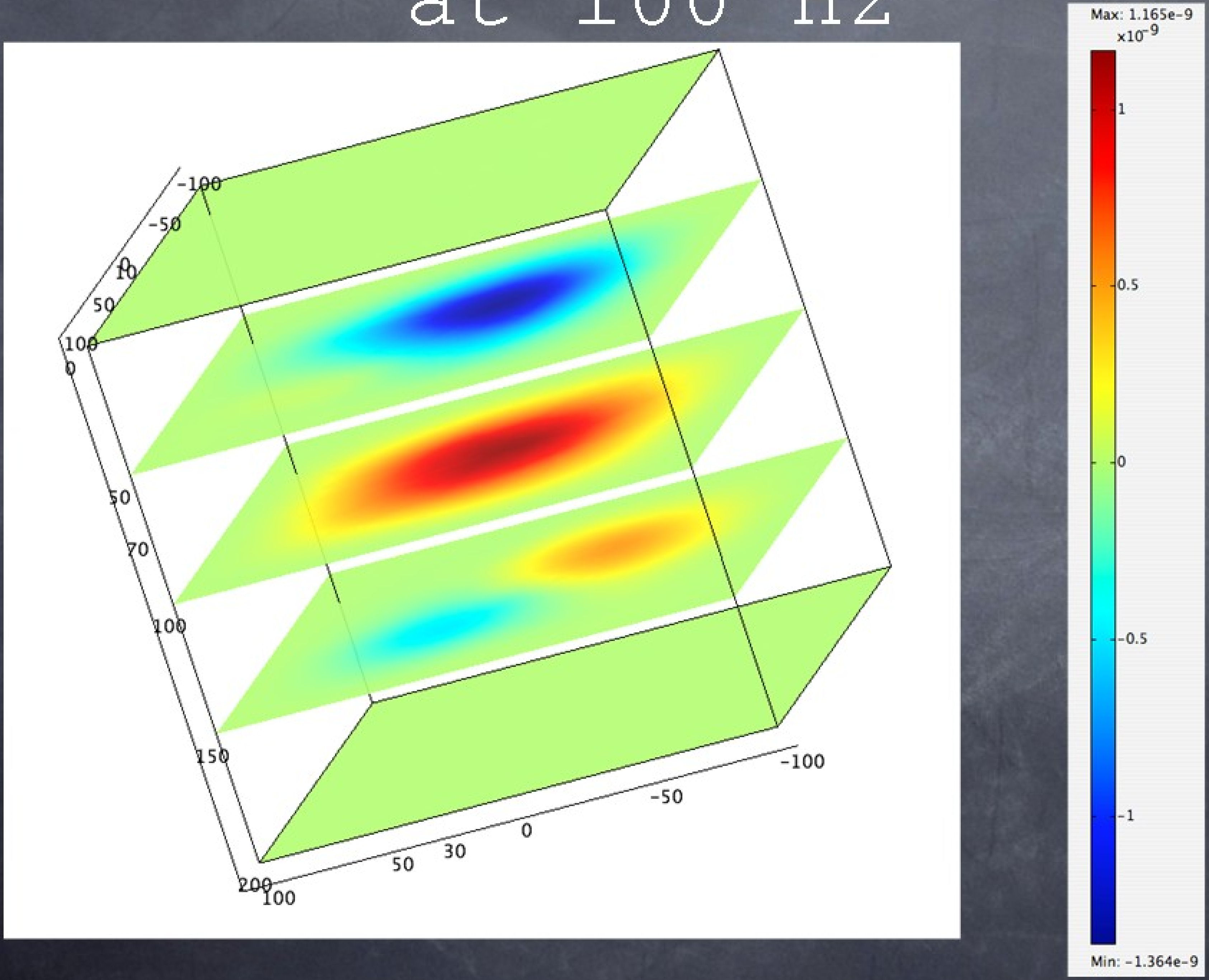


# Relative displacement

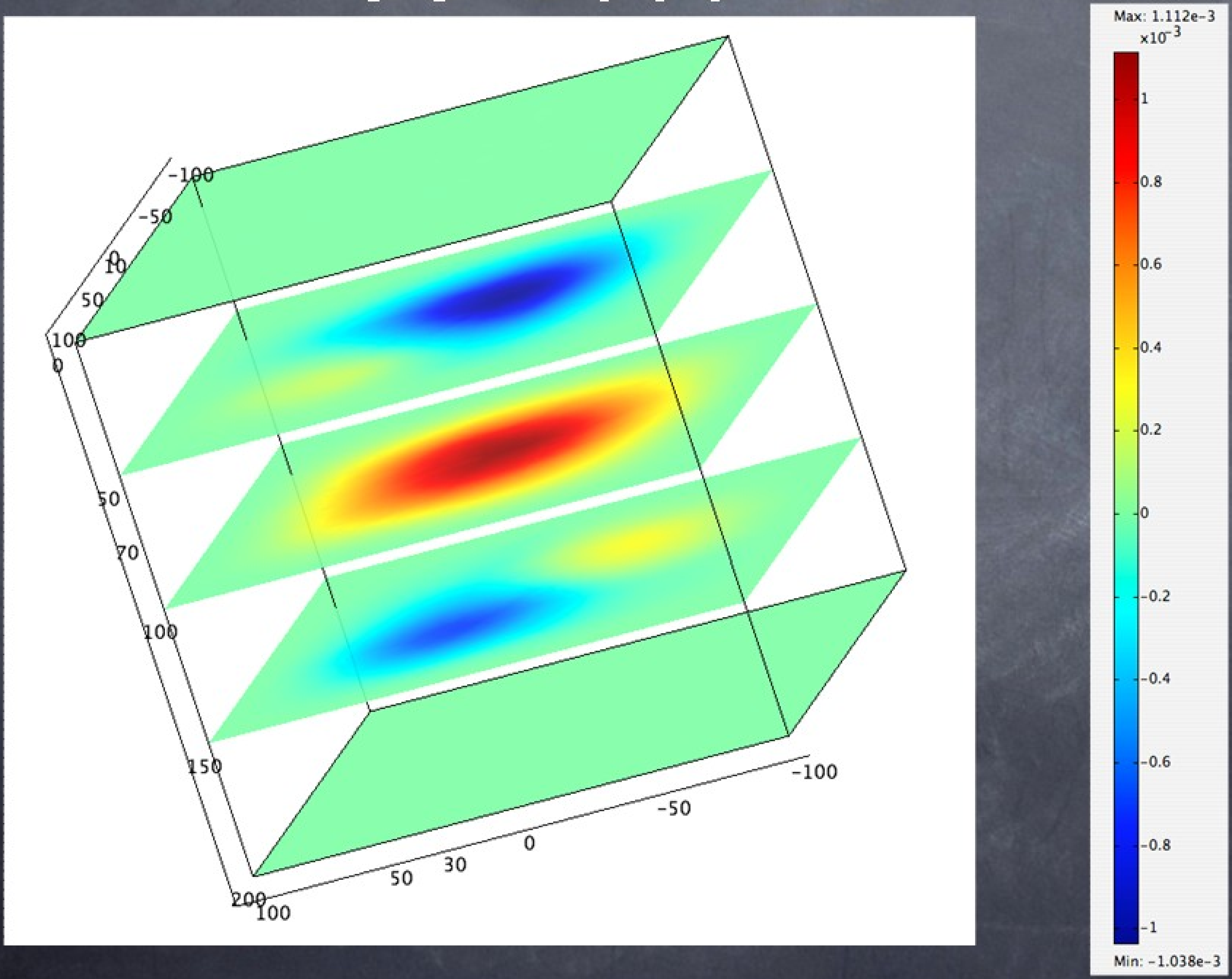
- Sub nm displacement at 1000 Hz



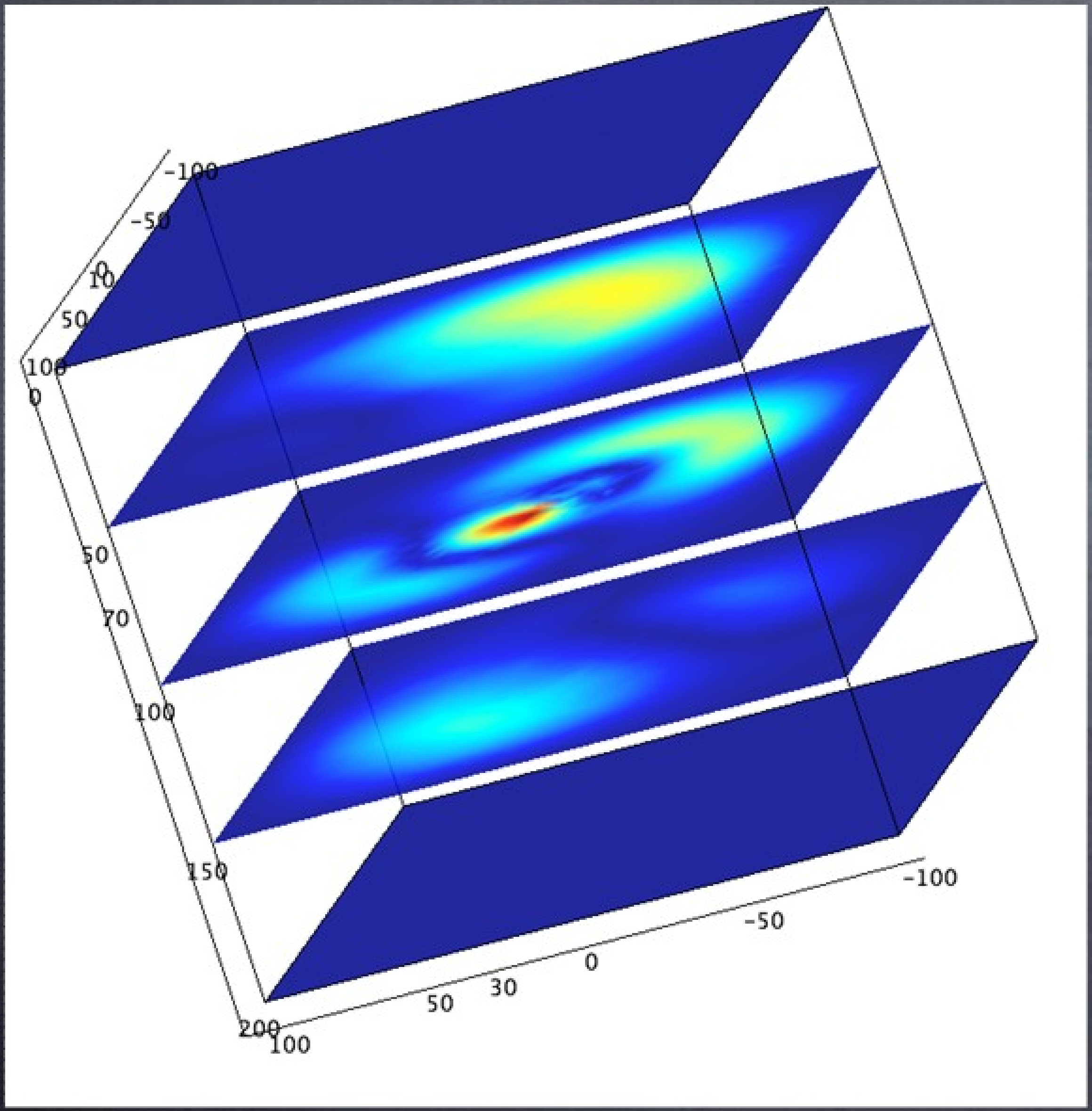
# Vertical electric field at 100 Hz

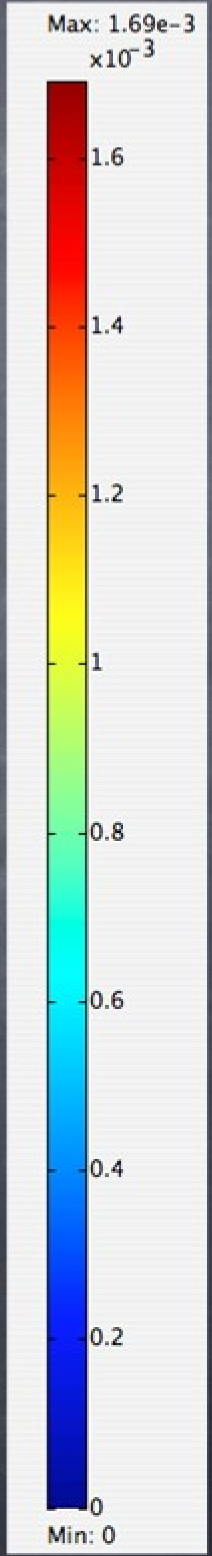


# Vertical electric field at 1000 Hz



# Magnitude of electric field at 1000 Hz



# Results

- Vertically-oriented oscillating electric dipoles are produced
- Vertical electric field strength increases 6 orders of magnitude from 100 to 1000 Hz
- Relative solid-liquid displacement is small and does not correlate with the electric field
- Conduction (electronic) current seems larger than streaming (ionic) current

# Future work

- Simulations with higher frequencies with layered earth model
- Analytical work on EM signals from dipoles at interface
- “Resonance frequency” of the dipole at the interface
- Field work: instrumentation and processing

We are looking for 1 graduate student

- Time-domain response signal

# Acknowledgments

This research project has been funded by AERI under COURSE program in 2004 for 3 years

CREWES is thanked for in-kind contributions and technical supports