Electroseismics for CO_2 storage and hydrocarbon reservoirs

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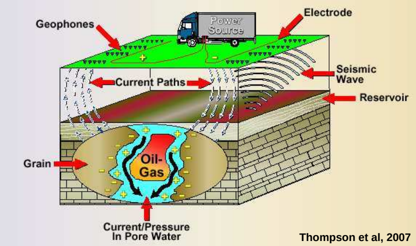
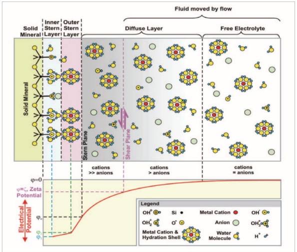
CONICET

Electroseismics: field experiments



- Electroseismic response in gas and oil reservoirs from about 1500 m depth.
- Signal between two and six orders of magnitude less than ambient noise.
- It is necessary to optimize the source power ($\sim$ megawatt), the injected signal (few thousands A), and the detection equipment (digital accelerometers).

Electroseismic Modeling I



Glover and Jackson, TLE, 2010

When an applied electric field acts on an electrolyte saturated porous material, besides driving σE, it acts as a body force on the excess charge, giving rise to a net fluid filtration; this is called *electro-osmosis* $\Rightarrow$ electroseismic phenomena.

Reciprocally, an applied pressure gradient generates an electric current; this is called *electro-filtration* $\Rightarrow$ seismoelectric phenomena.

Electroseismic modeling II

Assuming an $e^{+i\omega t}$ time dependence, Pride (1994) proposed

$$
\begin{aligned}
&(\sigma + i\epsilon\omega)E - \nabla \times H + L(\omega)\eta\kappa^{-1}\left[i\omega u^f - L(\omega)E\right] = -J_e^{ext},\\
&\nabla \times E + i\omega\mu H = -J_m^{ext},\\
&-\omega^2\rho_b u^s - \omega^2\rho_f u^f - \nabla\cdot\tau(u) = F^{(s)},\\
&-\omega^2\rho_f u^s + \eta\kappa^{-1}\left[i\omega u^f - L(\omega)E\right] + \nabla p_f = F^{(f)},\\
&\tau_{lm}(u) = 2G\,\varepsilon_{lm}(u^s) + \delta_{lm}\left(\lambda_c\,\nabla\cdot u^s + \alpha K_{av}\,\nabla\cdot u^f\right),\\
&p_f(u) = -\alpha K_{av}\,\nabla\cdot u^s - K_{av}\nabla\cdot u^f.
\end{aligned}
$$

ϕ porosity, ρ_s, ρ_f solid and fluid densities, $\rho_b = (1-\phi)\rho_s + \phi\rho_f$, η fluid viscosity, $\kappa(\omega)$ dinamic permeability

In the constitutive equations $\lambda_c = K_c - 2/3G$ and $K_c = K_m + \alpha^2 K_{av}$,

$$
\alpha = 1 - \frac{K_m}{K_s}, \qquad K_{av} = \left[\frac{\alpha-\phi}{K_s} + \frac{\phi}{K_f}\right]^{-1}.
$$

K_s, K_m and K_f: bulk moduli of the solid grains, the dry matrix and the fluid.

Electroseismic modeling III

2D Sources and Modes

- Infinite solenoid: J_m^{ext} generates electromagnetic fields $(E_x(x,z), E_z(x,z))$, and $H_y(x,z)$, coupled with solid displacements $(u_x^s(x,z), u_z^s(x,z))$ and fluid displacements $(u_x^f(x,z), u_z^f(x,z))$.
  This is the so-called PSVTM-mode, in which compressional and vertically polarized shear seismic waves (PSV-waves) are present.

- Infinite current line: J_e^{ext} generates electromagnetic fields $(H_x(x,z), H_z(x,z))$ and $E_y(x,z)$, coupled with solid displacements $u_y^s(x,z)$ and fluid displacements $u_y^f(x,z)$.
  This is known as the SHTE-mode, where only horizontally polarized seismic waves (SH-waves) are present.

Electroseismic modeling IV

Some assumptions

- We work in the seismic frequency range, then $\mathrm{Re}(\eta/\kappa(\omega)) \to \eta/\kappa_0$ and $\frac{1}{\omega}\mathrm{Im}(\eta/\kappa(\omega)) \to g_0 = 1.5\frac{\rho_f T}{\phi}$, T being the tortuosity factor so that the low-frequency Biot's equations are recovered.
- The electroseismic coupling coefficient L is assumed to be frequency independent,

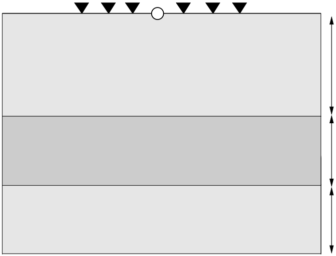
$$L_0 = -\frac{\phi}{T}\frac{\varepsilon_0 \kappa_f \zeta}{\eta}(1 - 2\frac{\widetilde{d}}{\Lambda}),$$

- $F^{(s)} = F^{(f)} = 0$, and $\omega\varepsilon/\sigma \ll 1$
- We consider lossy media using Liu's model.
- Electro-filtration feedback negligible; this decouples the EM fields from the poroviscoelastic response. (This makes calculations easier)

Scheme of the Finite Element Procedure

- Create a partition of the domain (elements).
- Transform original equations into a "weak form".
- Choose appropriate polynomial functions to approximate the solution in each element, (dofs).
- Transform the weak form into a linear sistem, and solve it. ($\sim 4 - 7 \times 10^7$ unknowns)

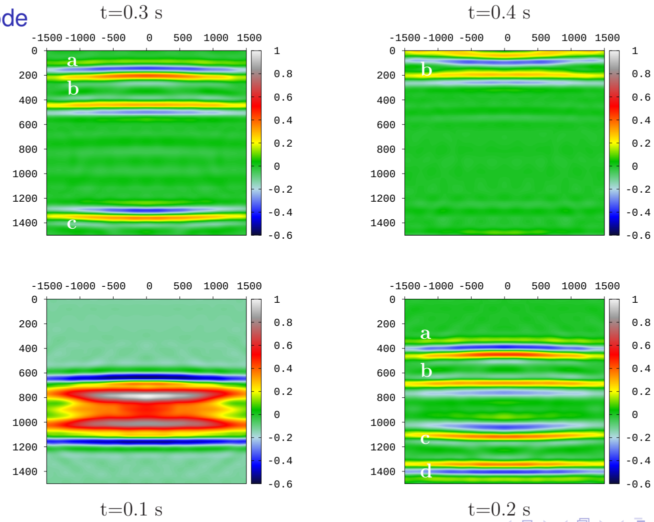
Single horizontal layer



	Medium 1	Medium 2 (layer)
σ (S/m)	0.1	0.01
ϕ (—)	0.2	0.33
K_s (Pa)	$4.5\ 10^{10}$	$6\ 10^{10}$
v_p (m/s)	3900	4800
v_s (m/s)	2130	2800
ρ_s (kg/m^3)	2600	2600
k_0 (m^2)	10^{-16}	10^{-11}
L_0	10^{-14}	$8.16\ 10^{-9}$
Q (—)	90	90
ρ_f (kg/m^3)	1000	1000
η (kg/(m s))	0.001	0.001
K_f (Pa)	$2.25\ \ 10^9$	$2.25\ \ 10^9$
S_f (—)	1	1

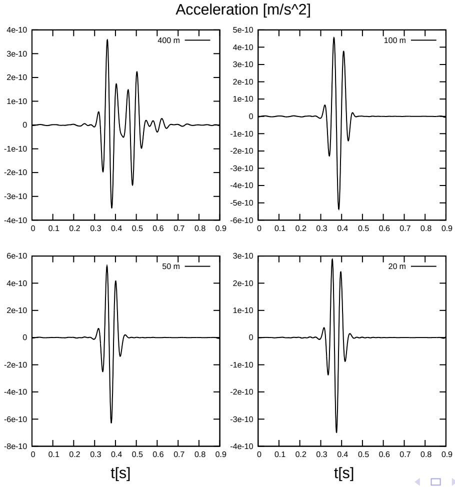
Single horizontal layer

SHTE-mode



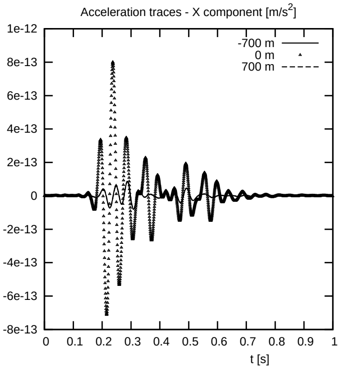
Single horizontal layer

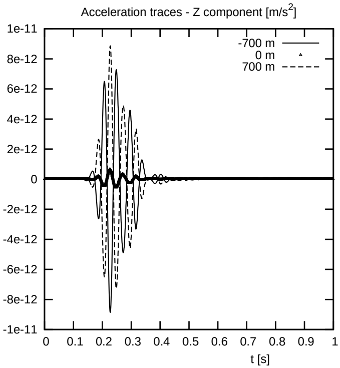
Different layer widths, SHTE-mode



Single horizontal layer

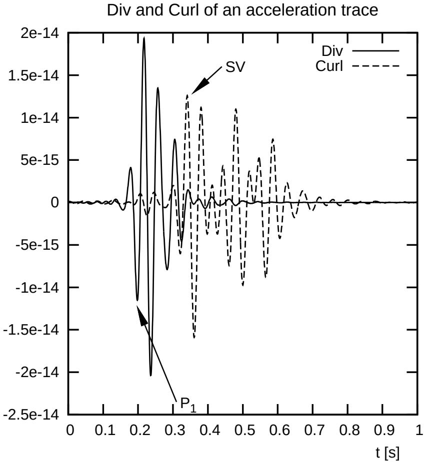
PSTVM-mode



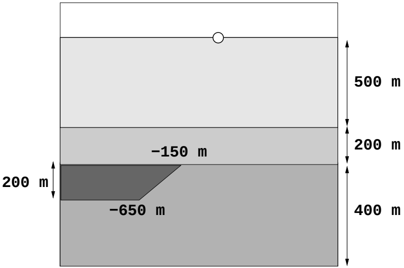


Single horizontal layer

PSTVM-mode



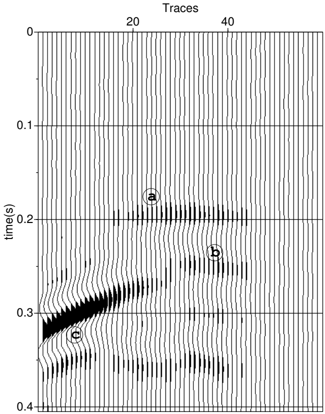
Wedge

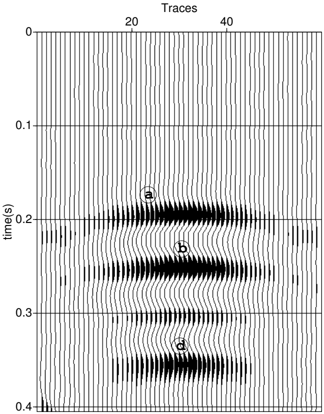


	First Layer	Second layer	Third layer	Wedge
σ^c (S/m)	0.01	0.1	0.01	0.001
ϕ (—)	0.2	0.25	0.2	0.2
K_s (Pa)	$3.7\ 10^{10}$	$2.5\ 10^{10}$	$3.7\ 10^{10}$	$3.7\ 10^{10}$
v_p (m/s)	2500	2600	3000	3000
v_s (m/s)	1400	1450	1800	1800
ρ_s (kg/m^3)	2650	2650	2650	2650
k_0 (m^2)	10^{-13}	10^{-16}	10^{-13}	10^{-13}
L_0	$3.2\ 10^{-15}$	$1.5\ 10^{-9}$	$3.3\ 10^{-9}$	$3.3\ 10^{-9}$
Q (—)	30	50	30	30
ρ_f (kg/m^3)	1000	1000	1000	0.88
η (kg/(m s))	0.001	0.001	0.001	1.10^{-5}
K_f (Pa)	$2.25\ 10^9$	$2.25\ 10^9$	$0.1\ 10^9$	$0.1\ 10^9$
S_f (—)	1	1	1	0.75

Surface gather

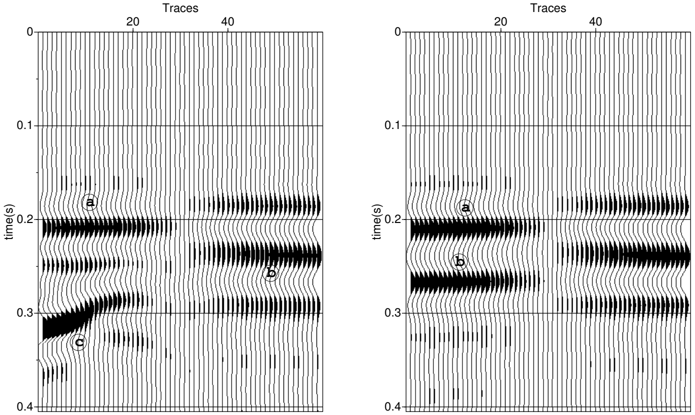
x-component acceleration





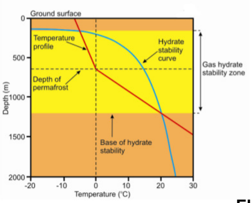
Surface gather

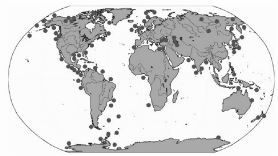
z-component acceleration



Methane hydrates (GH) ...

- ...form stable ice-like crystals in permafrost regions and beneath the ocean floor along continental margins.





Ellis, 2008

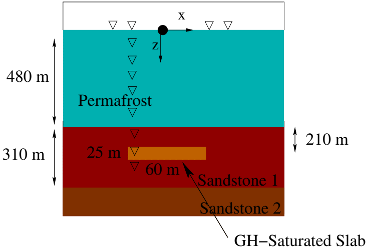
- ...are considered as a potentially huge energy resource.
- ...have the highest energy density of any naturally occurring form of methane (about 160 times that of methane gas)
- ...decrease the electrical conductivity of the medium.

Composite Media

We use an extended Biot theory for composite matrix rocks with non uniform porosity distributions.

- The solid matrix can be formed by mixtures of different mineral grains.
- A fraction of the GH (ice) is assumed to form a second matrix occupying the pore space , and the rest of it is assumed to cement the mineral grains.
- Letting $V = (V_{gh}^{c} + V_{gh}^{nc}) + V_{mg} + V_f$, $V_p = V - V_{mg}$, $\phi_a = V_p/V$; and $C_{gh} = V_{gh}^{c}/V_{gh}$,cementation coefficient, $S_{gh} = V_{gh}/V_p$ GH saturation, all (Biot) model parameters are obtained in terms of C_{gh}, S_{gh}, ϕ_a, K_{mg}^{j} and μ_{mg}^{j} forming the solid matrix; and K_{gh}, μ_{gh}.

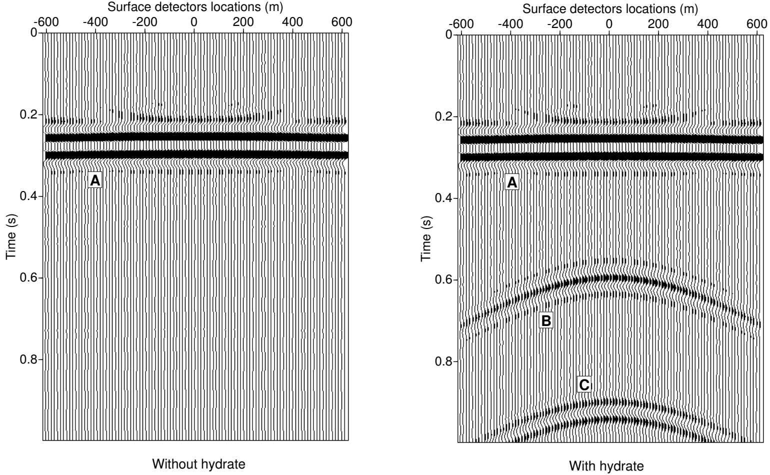
The Model



	Permafrost	**Sandstone**	**Slab** $(S_{gh} = 0.1)$	**Slab** $(S_{gh} = 0.8)$
ϕ	0.025	0.25	0.225	0.05
V_p m/s	4100	2250	2930	4080
V_s m/s	2150	690	1580	2180
σ S/m	$8 \cdot 10^{-3}$	0.025	$8 \cdot 10^{-3}$	10^{-3}
L_0 A/(Pa m)	10^{-16}	$4.6 \cdot 10^{-9}$	$4.15 \cdot 10^{-9}$	$9.4 \cdot 10^{-10}$

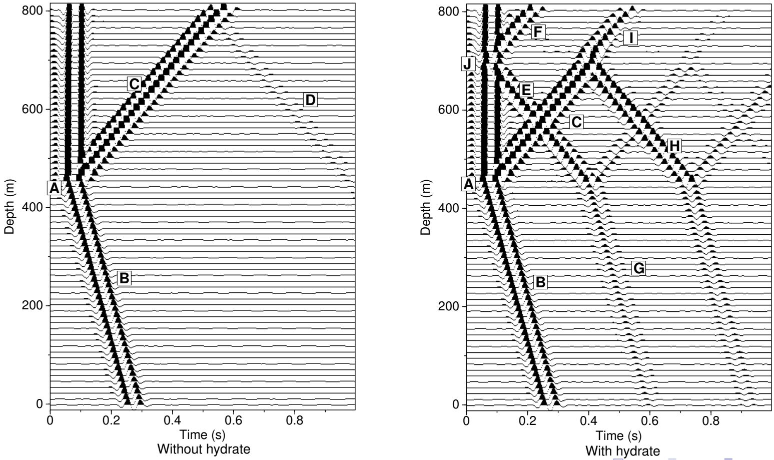
SHTE-mode

Acceleration surface gather



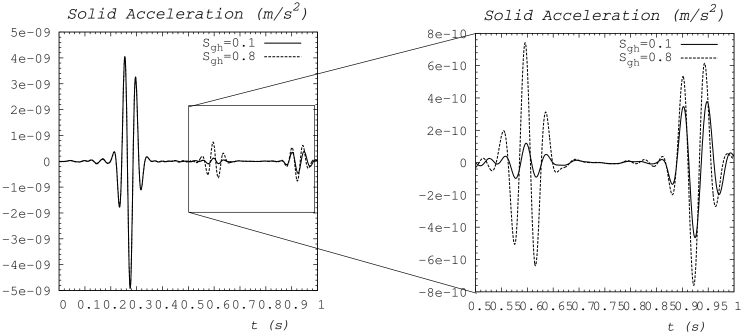
SHTE-mode

Acceleration well gather



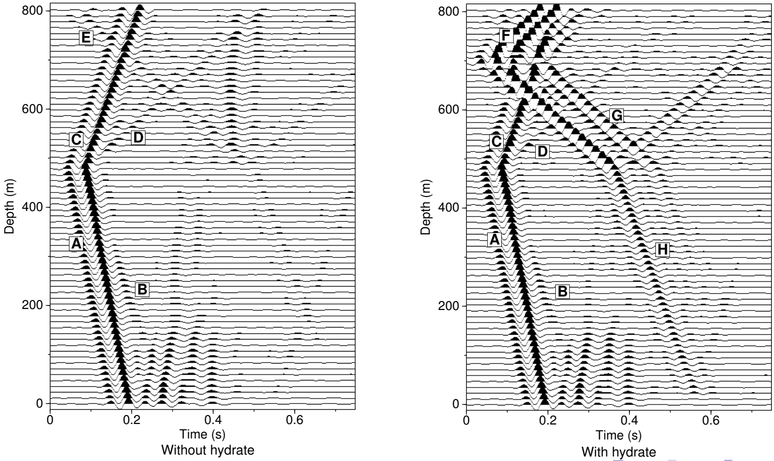
SHTE-mode

Acceleration surface trace for $S_{gh} = .1$ and $S_{gh} = .8$



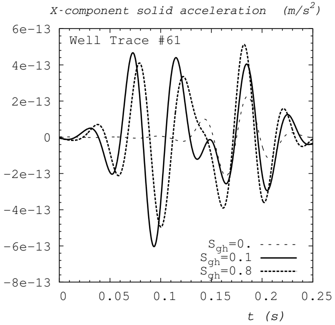
PSVTM-mode

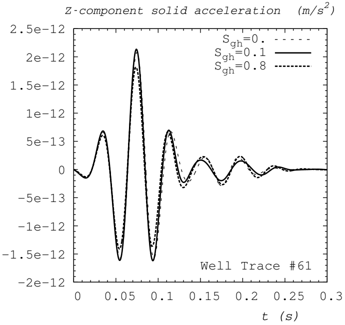
Acceleration (x-component) well gather



PSVTM-mode

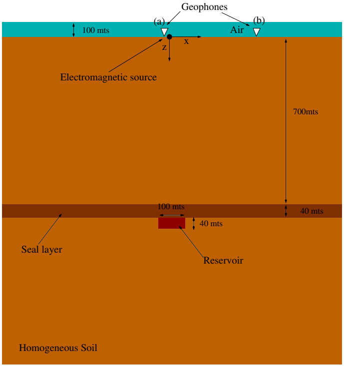
Acceleration well traces for for $S_{gh} = .1$ and $S_{gh} = .8$





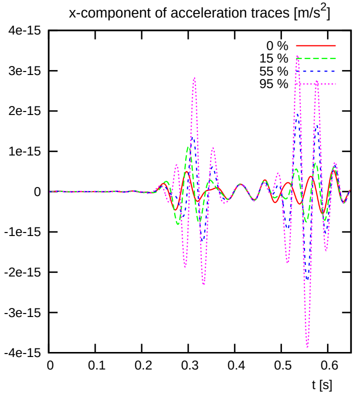
CO_2 storage monitoring

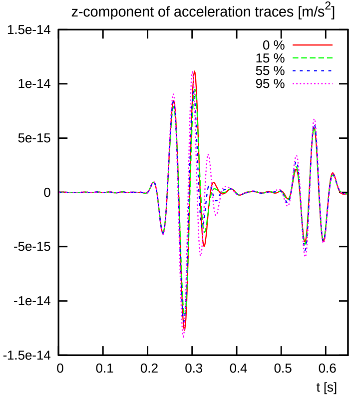
The Model



CO_2 storage monitoring

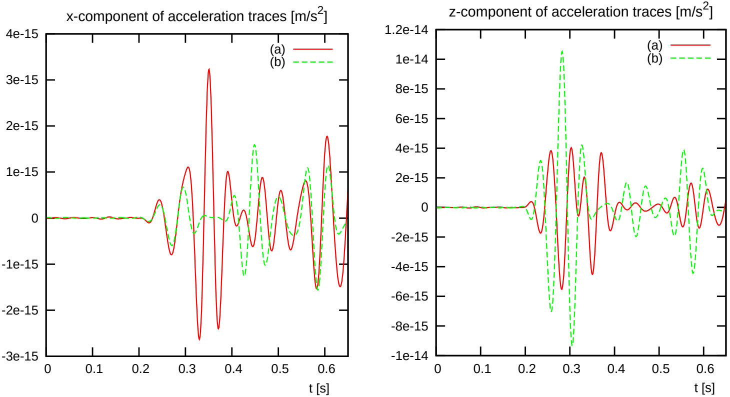
PSVTM mode, acceleration traces





CO_2 storage monitoring

PSVTM mode, acceleration traces



Summary

- We have developed a numerical tool to simulate electroseismic (and seismoelectric) phenomena.
- It was observed that the response is sensitive to changes in fluid conductivities (mixtures of gas an brine).
- We have shown that methane hydrates can be detected by means of electroseismics on land in permafrost regions.
- We have observed that the seismic response is sensitive to methane hydrate concentration
- Preliminar results indicate that it could be very interesting to consider electroseismics/ seismoelectrics as a monitoring tools for CO_2 storage sites.
- Heaps of work ahead!