Modeling the seismoelectric electrokinetic coupling: A new approach to up-scale the frequency-dependent effective excess charge density

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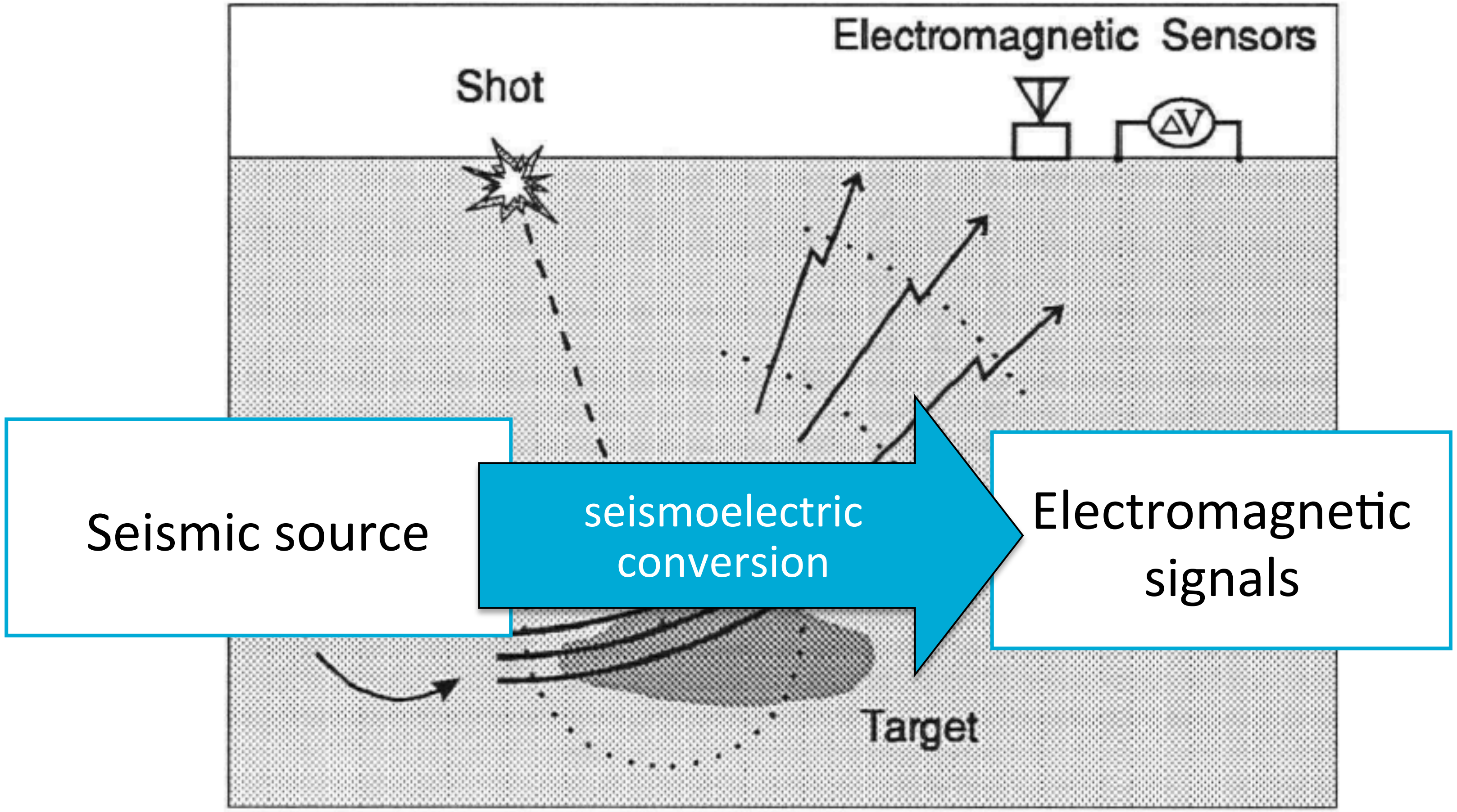
Presentation outline

- **The seismoelectrical method**
  - Definitions & contributions to the signal
  - Cross-borehole example
- **Petrophysical developments**
  - Up-scaling electrokinetic coupling
  - Confrontation with laboratory experiments
  - Modeling perspectives
- **Conclusions and perspectives**

The seismoelectric method – basic definitions

Seismic waves propagating in geological media induce measurable electrical potential distribution



Seismoelectric signals – basic definitions

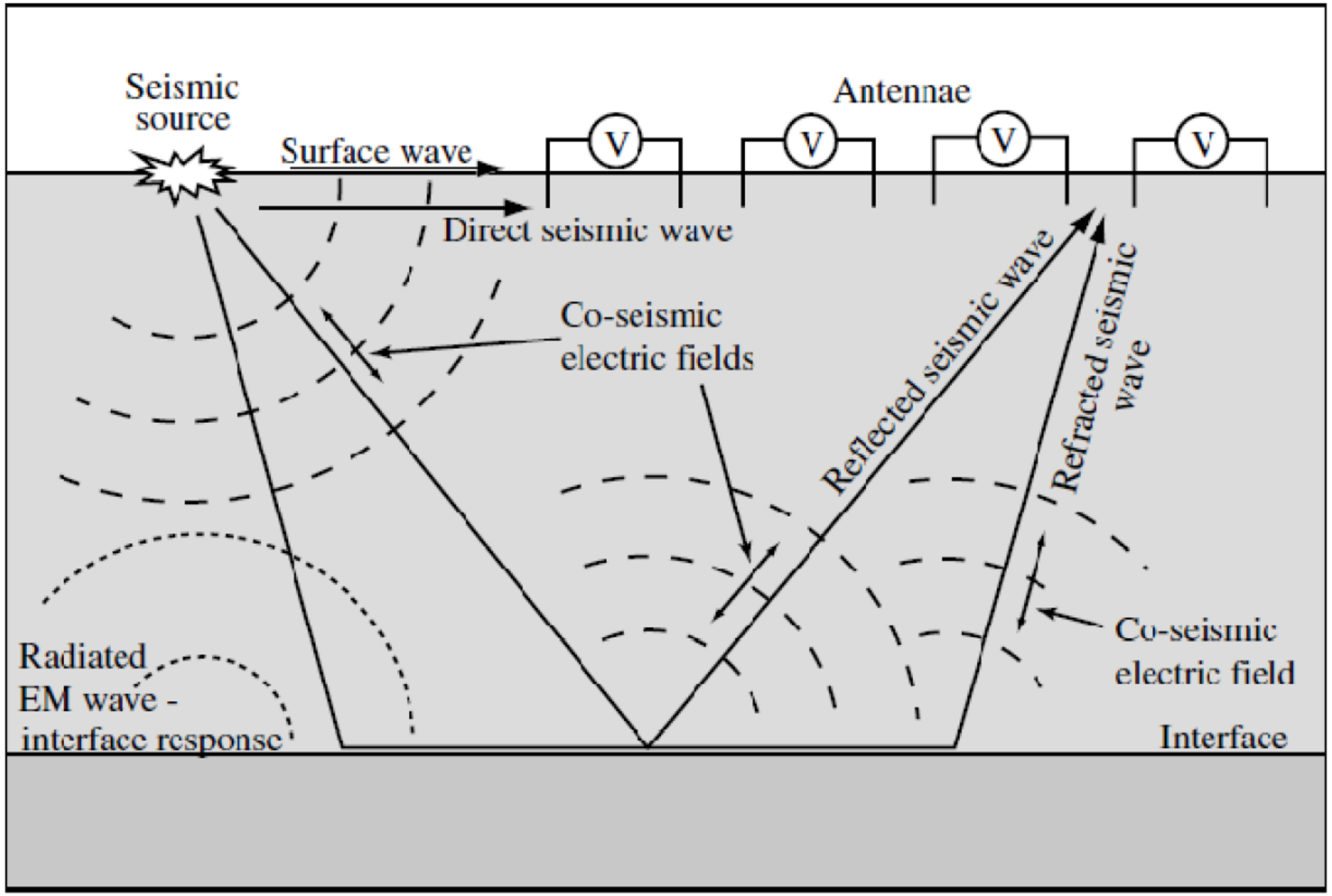
Combining seismic and electrical methods

The seismoelectric method is the measurements of electromagnetic signals that arise when seismic waves stress earth materials:

- Co-seismic signal (travel with the wave)
- Interface signal (EM response to a contrast in rock properties)
- Mesoscopic signal (generated by WIFF)

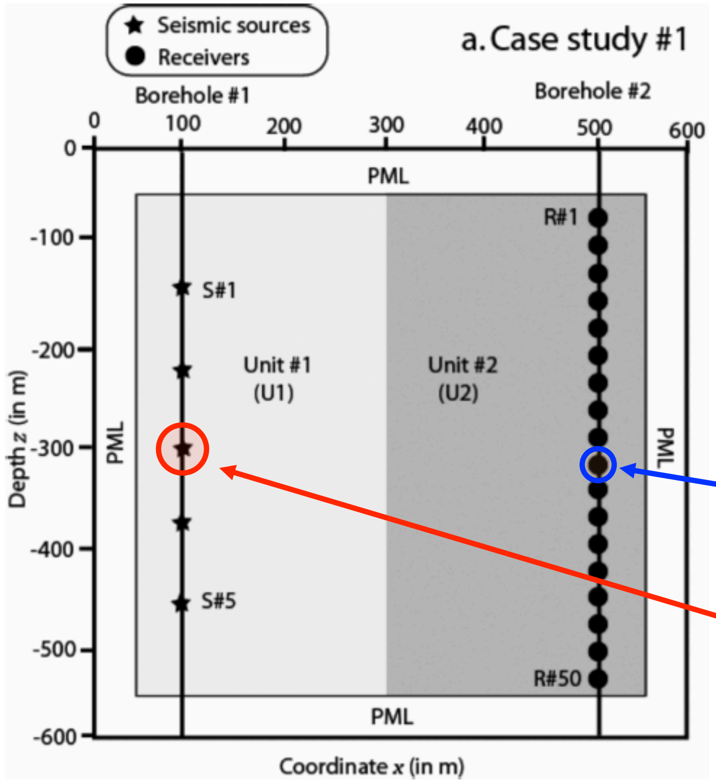
Measurements

- 1, 2 or 3D imaging
- Borehole logging
- Time lapse



Seismoelectric – cross-borehole example

Illustration with a numerical example (Araji et al., 2012)



Araji et al. (2012)

Cross-boreholes seismoelectric investigation

Two homogeneous units

Two boreholes:

- borehole #1: shooting of the seismic source
- borehole #2: measurements (displacement & electrical potential)

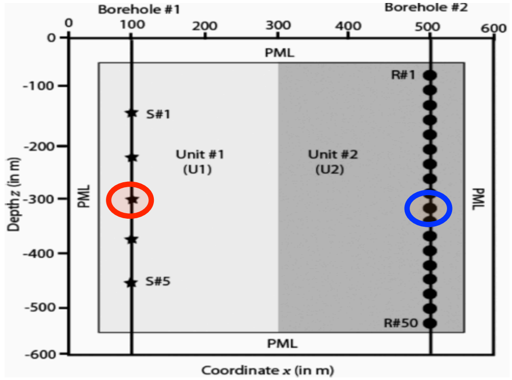
Electrodes (El#25)

Seismic source

Seismoelectric – cross-borehole example

Illustration with a numerical example (Araji et al., 2012)

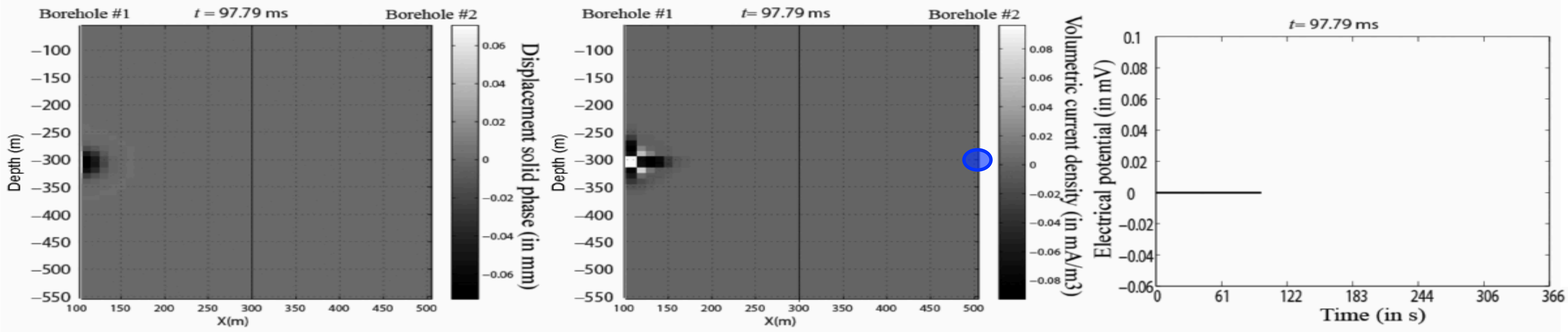
Cross-boreholes seismoelectric investigation (t = 98 ms)



Seismic snapshot

Electrical current density

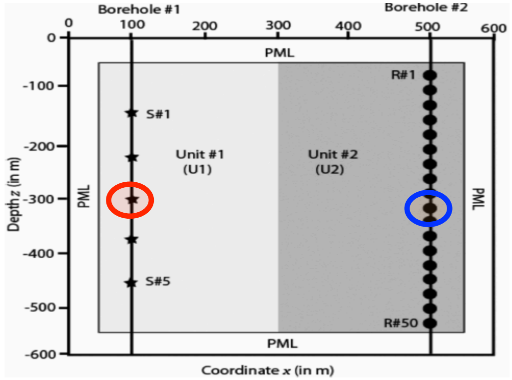
Electrical potential at El#25



Araji et al. (2012)

Seismoelectric – cross-borehole example

Illustration with a numerical example (Araji et al., 2012)

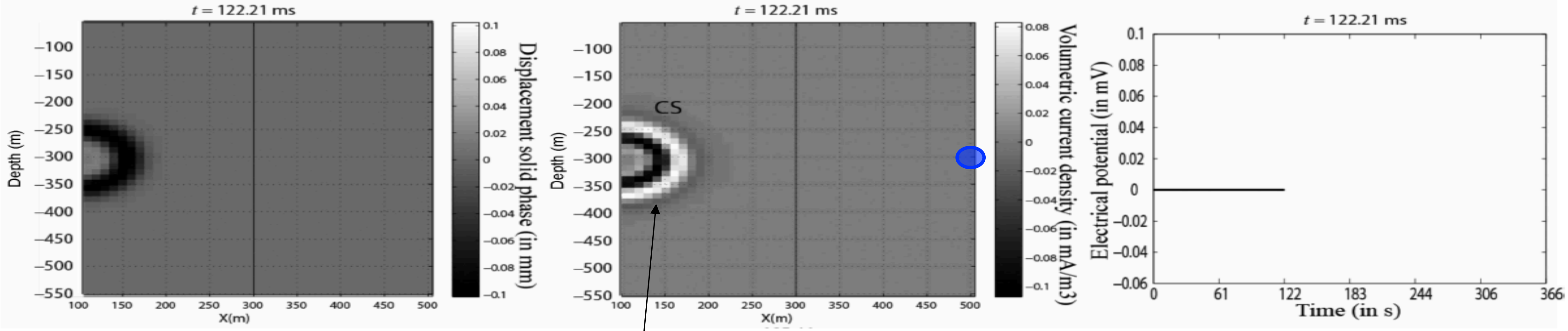


Cross-boreholes seismoelectric investigation (t = 122 ms)

Seismic snapshot

Electrical current density

Electrical potential at El#25



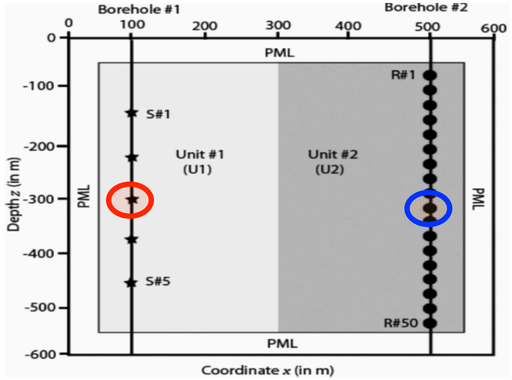
Araji et al. (2012)

CS: Co-Seismic signal

Seismoelectric – cross-borehole example

Illustration with a numerical example (Araji et al., 2012)

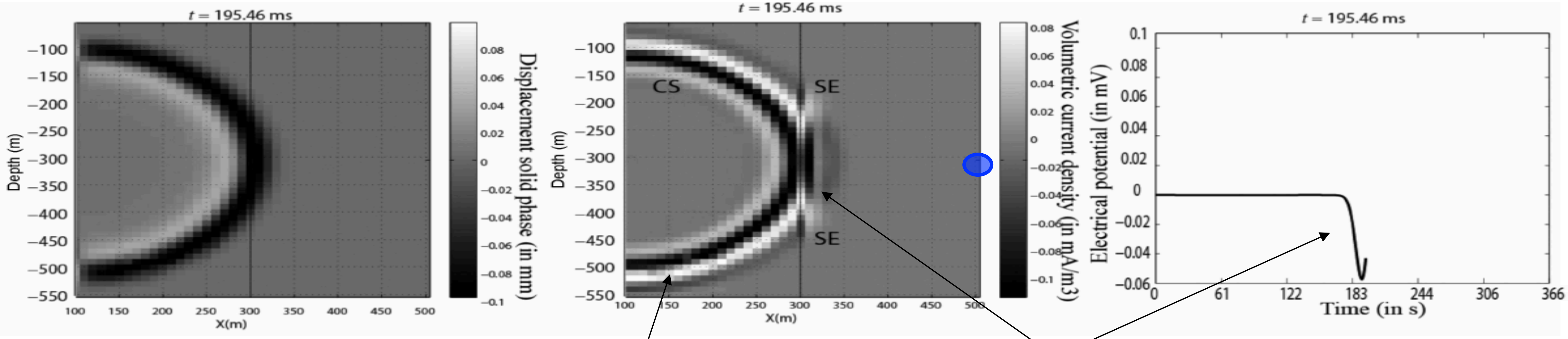
Cross-boreholes seismoelectric investigation (*t* = 195 ms)



Seismic snapshot

Electrical current density

Electrical potential at El#25



Araji et al. (2012)

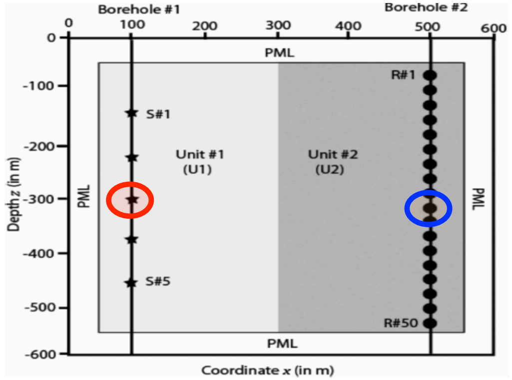
CS: Co-Seismic signal

SE: Interface signal

Seismoelectric – cross-borehole example

Illustration with a numerical example (Araji et al., 2012)

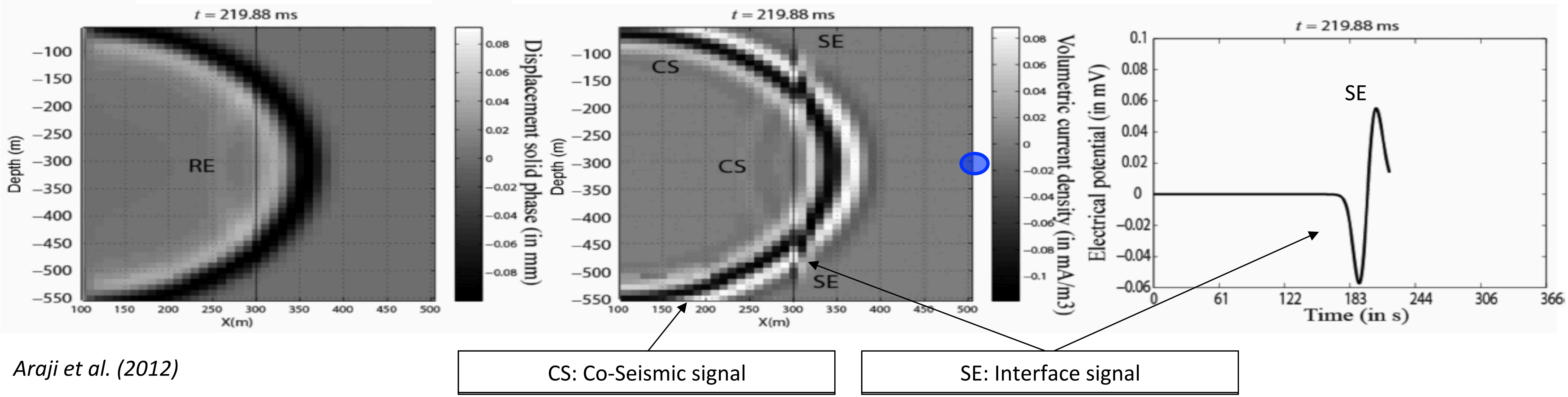
Cross-boreholes seismoelectric investigation (t = 220 ms)



Seismic snapshot

Electrical current density

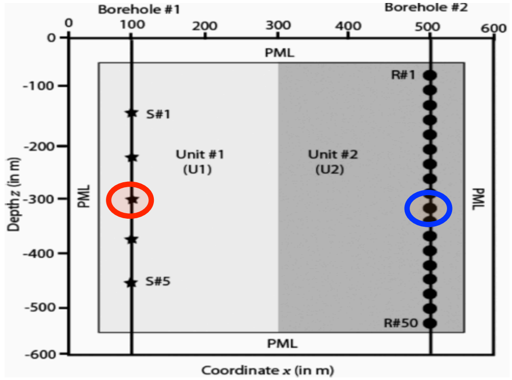
Electrical potential at El#25



Araji et al. (2012)

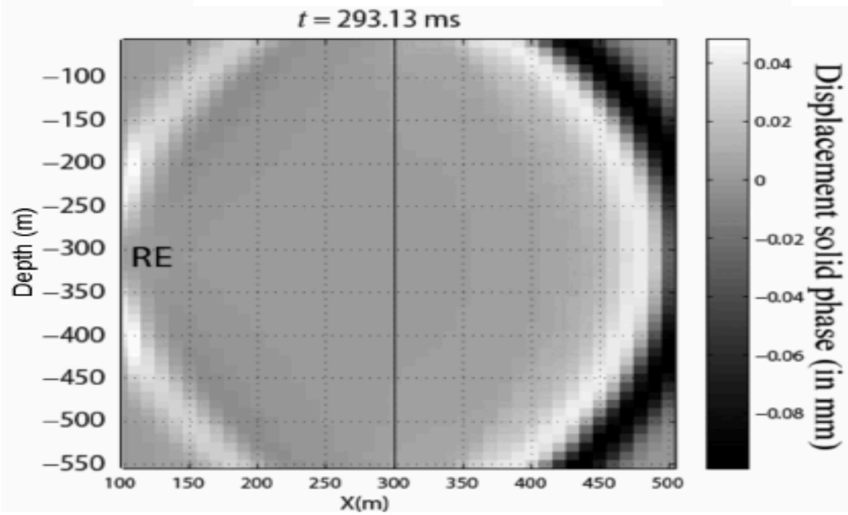
Seismoelectric – cross-borehole example

Illustration with a numerical example (Araji et al., 2012)

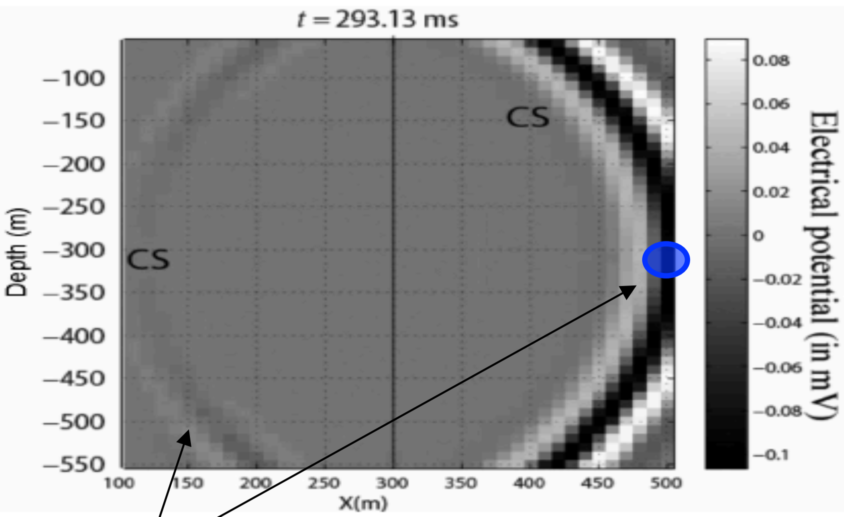


Cross-boreholes seismoelectric investigation (t = 293 ms)

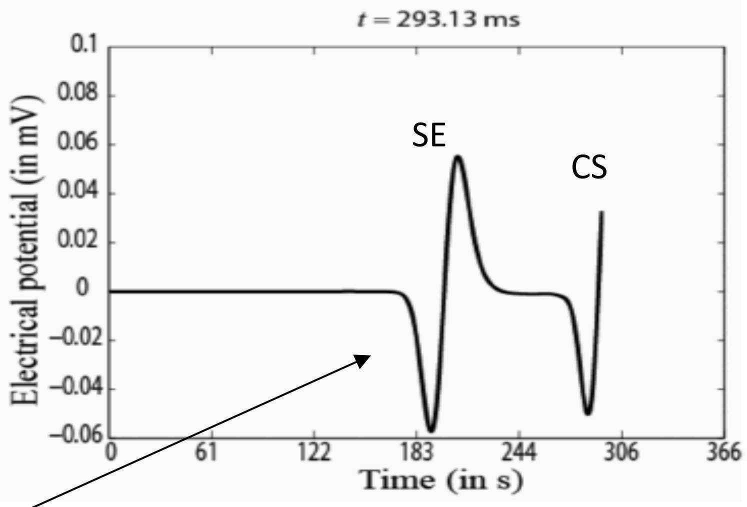
Seismic snapshot



Electrical current density



Electrical potential at El#25



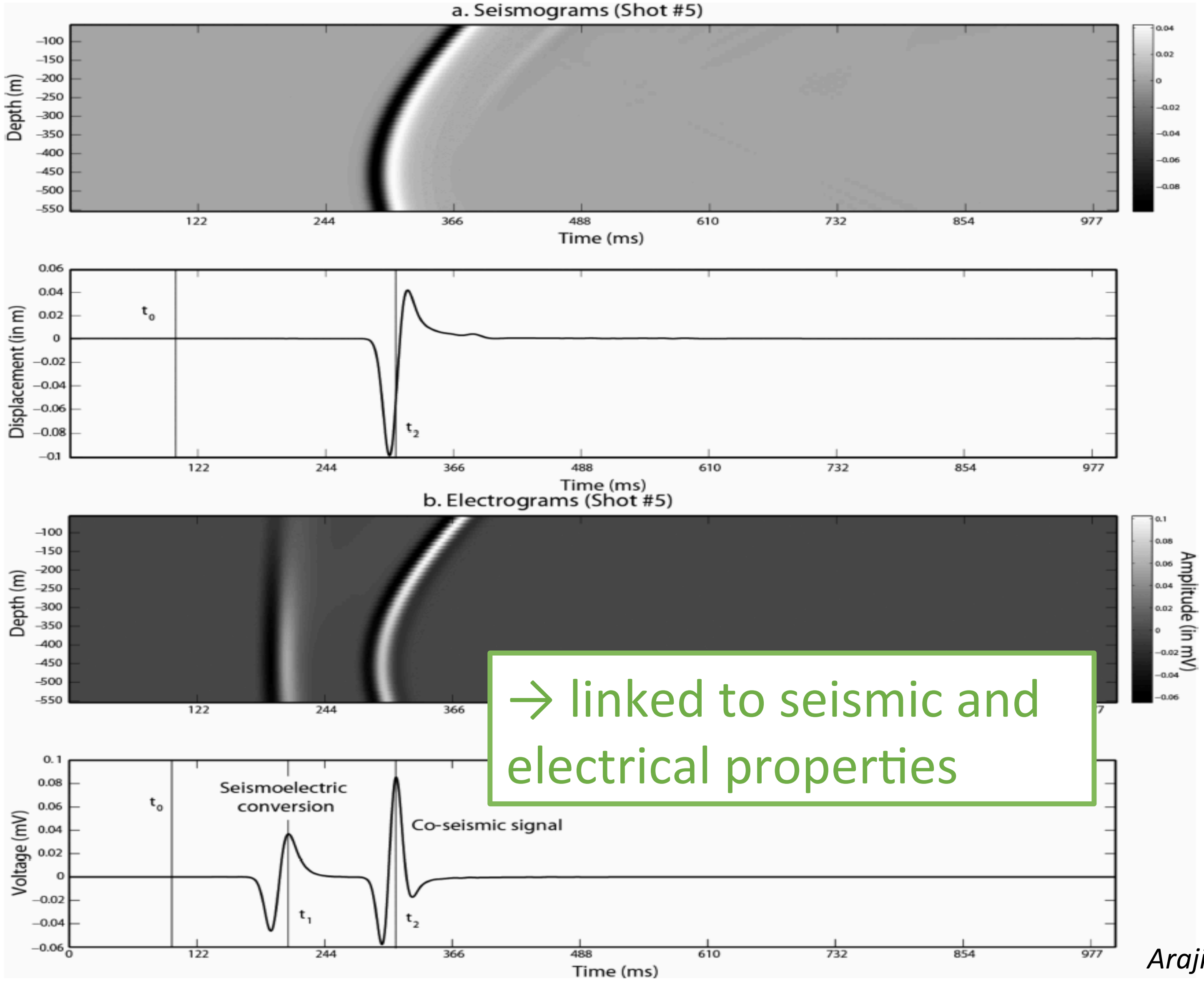
Araji et al. (2012)

CS: Co-Seismic signal

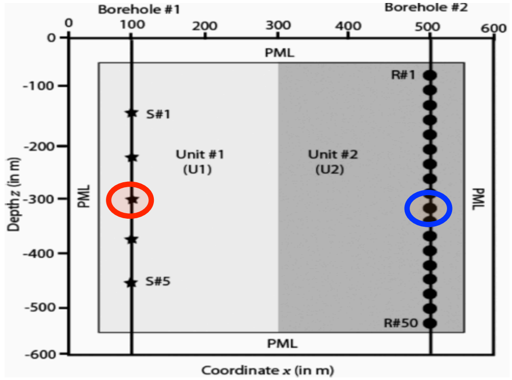
SE: Interface signal

Seismoelectric – cross-borehole example

Illustration with a numerical example (Araji et al., 2012)



→ linked to seismic and electrical properties



Seismogram

Displacement

Gives informations on wave velocity in the medium (averaged value)

Electrogram

Electrical potential

Gives information on wave velocity and the presence of mechanic or electrical properties interfaces (contrasts in medium properties)

Araji et al. (2012)

Seismoelectric – towards a quantitative use of the signal

Seismoelectrical signal contains information on mechanical and electrical parameters

Real interest for resources and reservoir characterization

Seismoelectric signals

⟷ Petrophysics ⟷

Rock /reservoir properties
Fluid saturation (water, oil, gas)
Porosity / permeability
Pore water salinity
…

Structure / properties contrasts
Lithology sequences
Fracturation / fissuration

How to extract relevant and quantitative information about the geological medium of interest (reservoir, critical zone, contaminated area) from seismoelectric signals ?

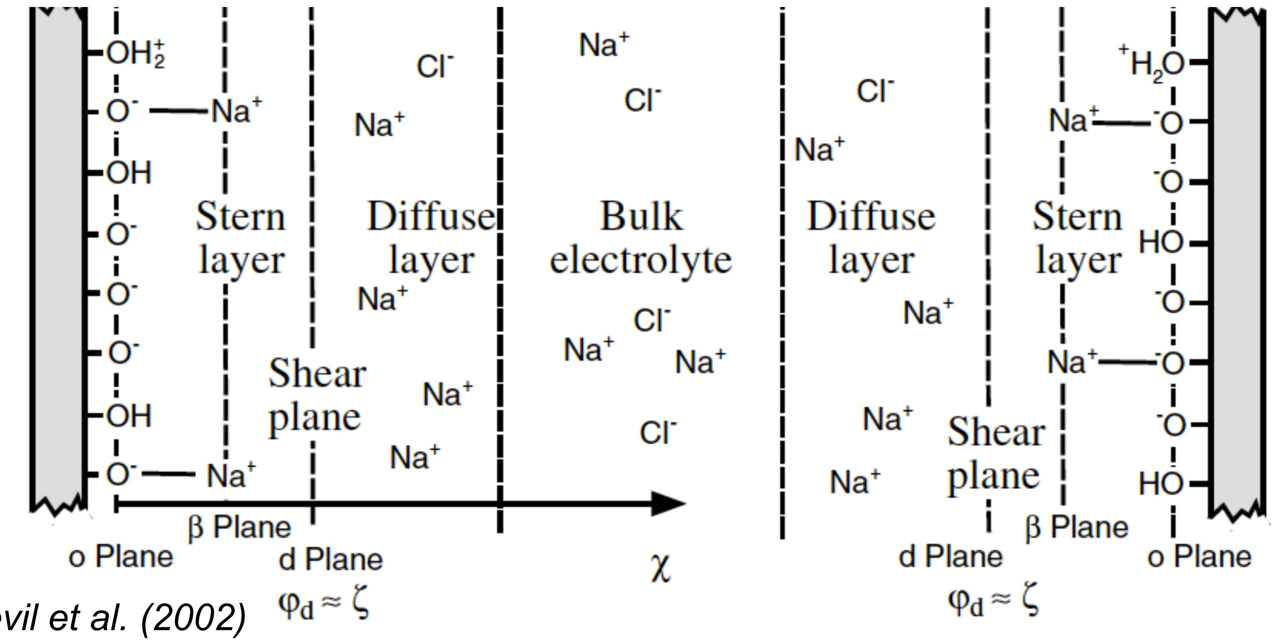
The electrokinetic nature of seismolectric conversion

Seismoelectric conversion is related to electrokinetic coupling phenomena
(e.g., Frenkel 1944, Packard 1953, Pride 1994, Revil et al. 2013, …)

Mineral surfaces are charged (often negatively)

↓ Electro-neutrality of the system

Excess of charges in the pore water → Distributed in layers:
- Stern layer
- diffuse layer



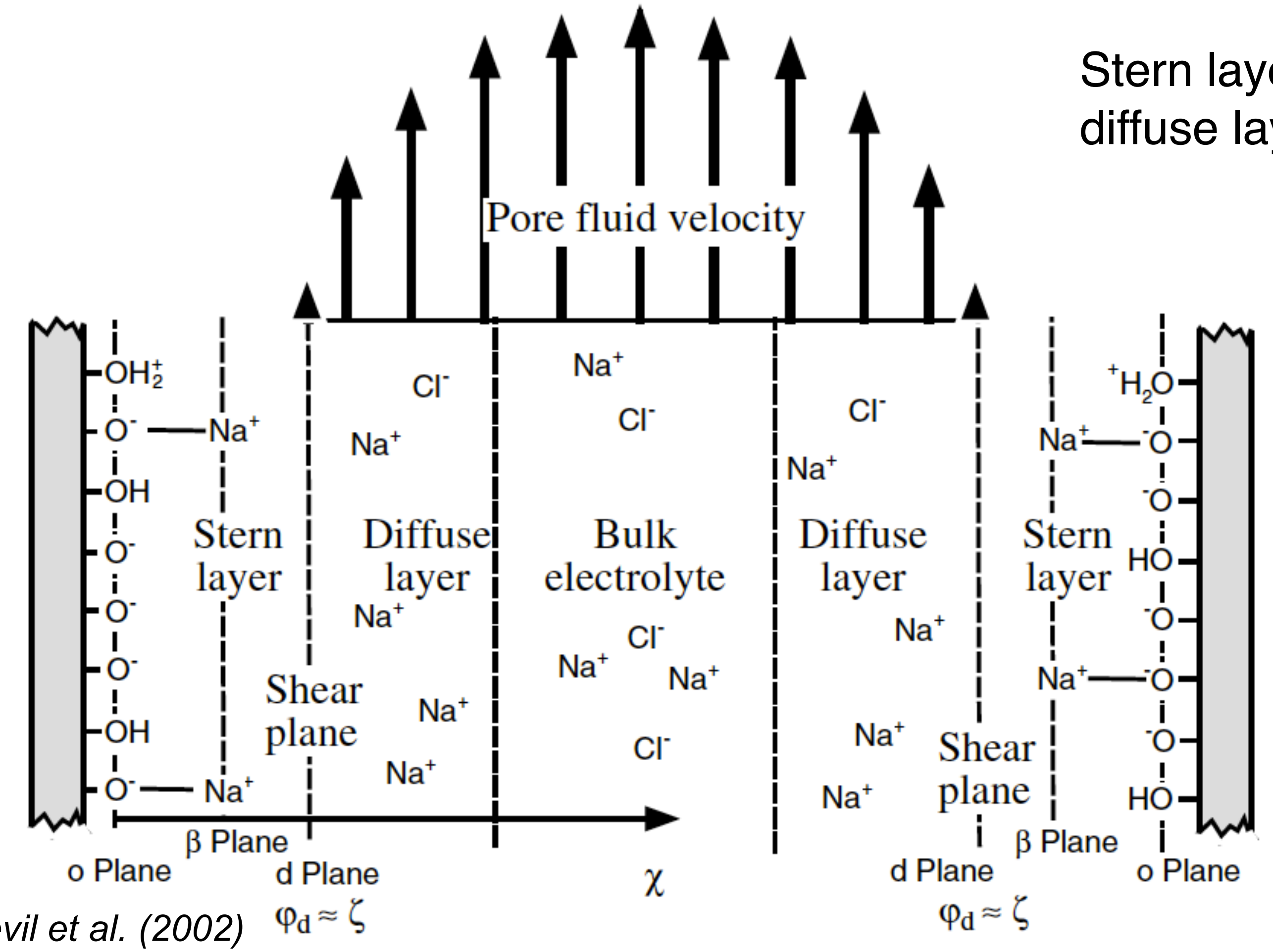
Revil et al. (2002)

Petrophysical developments for seismoelectrics

Seismoelectric conversion is related to electrokinetic coupling phenomena
(e.g., Frenkel 1944, Packard 1953, Pride 1994, Revil et al. 2013, …)

When the water flows in the pores the charges are dragged (relative fluid velocity)

Stern layer: immobile
diffuse layer: ~ mobile

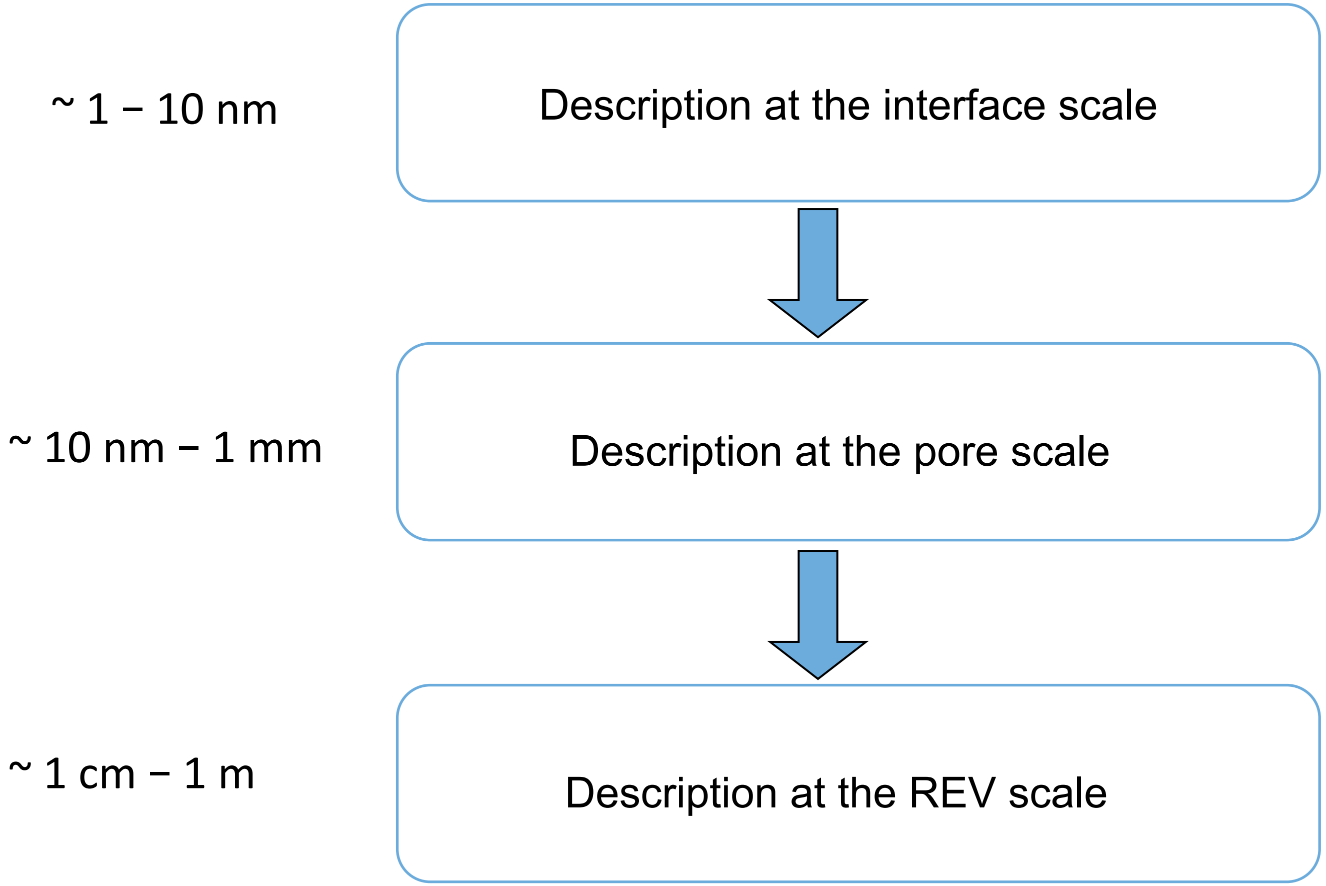


Revil et al. (2002)

Excess charge:
Sum of the ionic charges present in the diffuse layer

A new up-scaling approach: from the nm to the REV scale

Up-scaling framework proposed in Jougnot et al. (2012) for self-potential (f = 0 Hz) and Jougnot (2019) for seismoelectrics



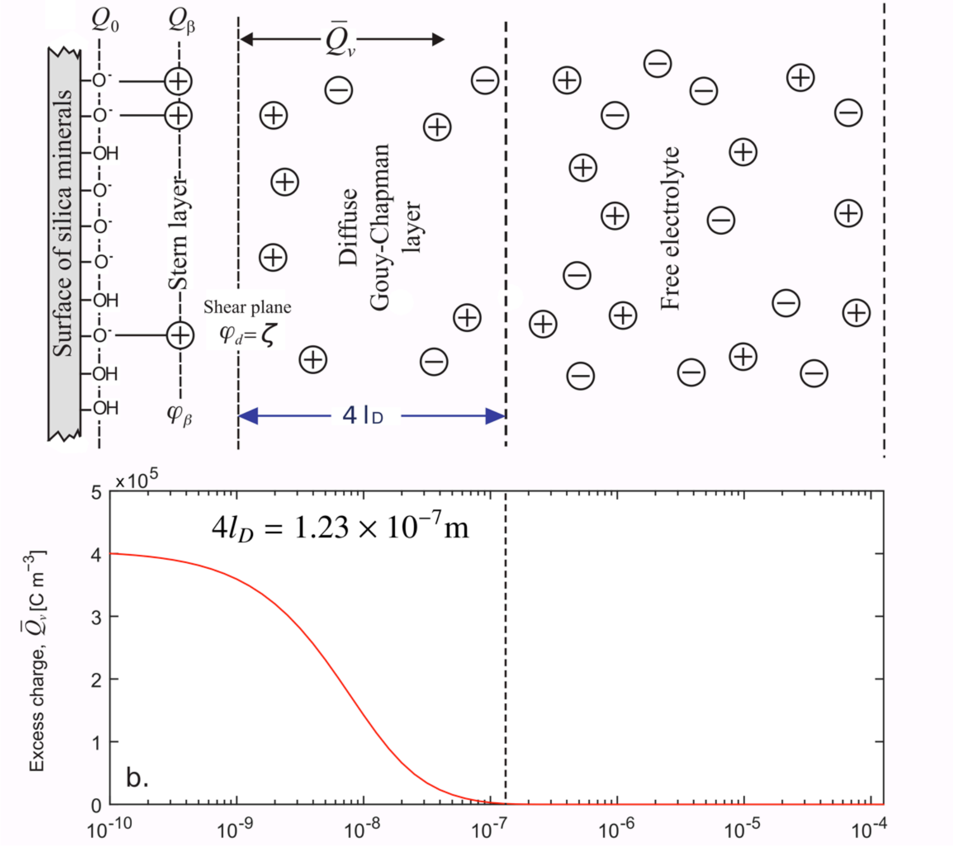
Description of the EDL

Up-scaling framework (Jougnot, 2019)

~ 1 – 10 nm

Description at the interface scale

Description of the EDL



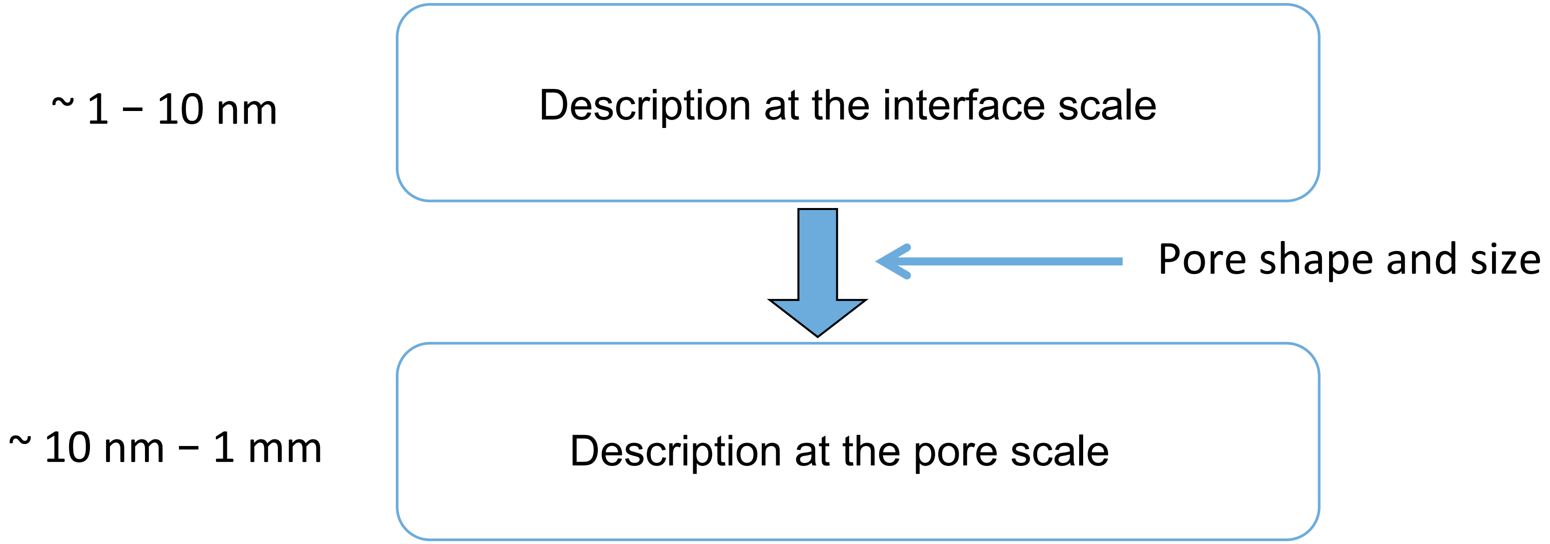
Electrical Double Layer (EDL)

Description of the electrical charge distribution in the EDL:

- diffuse layer: excess charge $\bar{Q}_v > 0 \text{ C m}^{-3}$
- free electrolyte $\bar{Q}_v = 0 \text{ C m}^{-3}$

Description at the pore scale

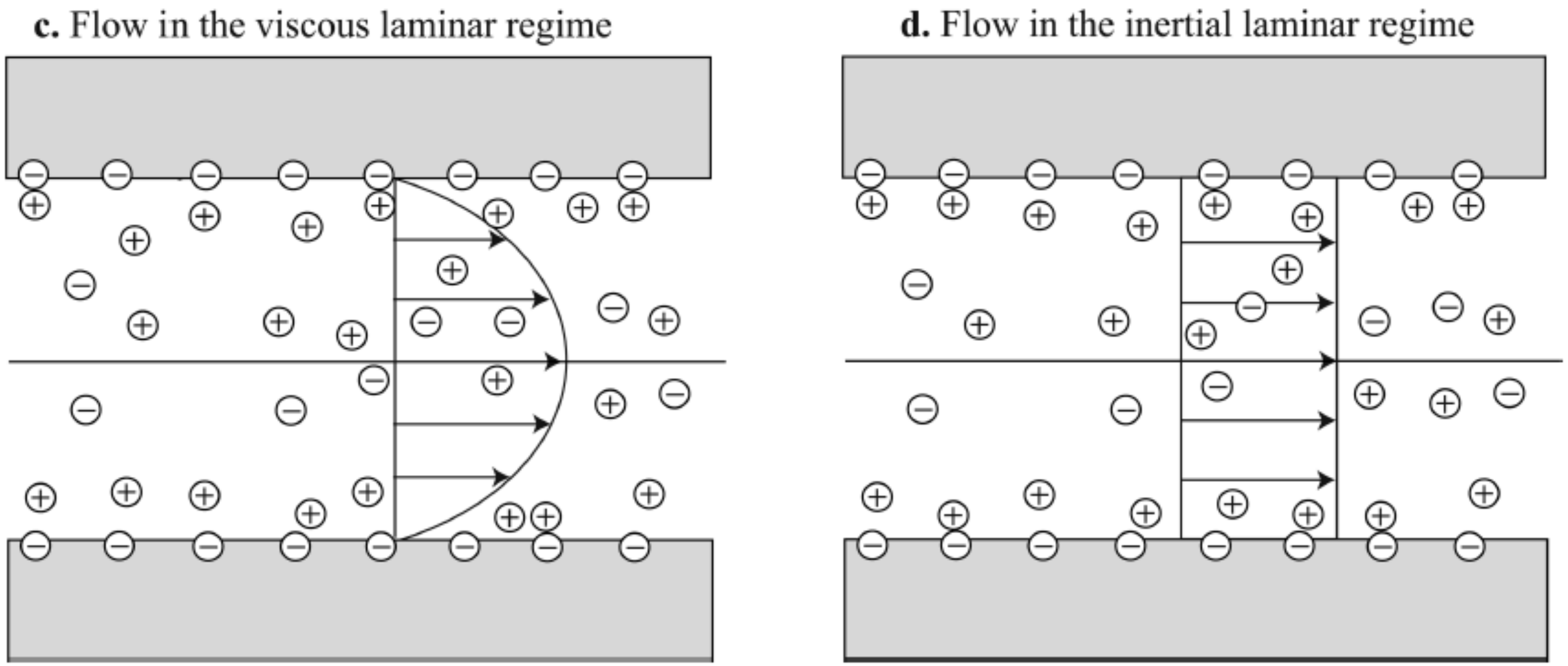
Up-scaling framework (Jougnot, 2019)



Petrophysical developments for seismoelectrics

Effect of the frequency on the electrokinetic coupling

What's happening at the pore scale ?



DC frequency (f = 0 Hz) High frequency ($f = \infty$ Hz)

Revil and Mahardika (2013)

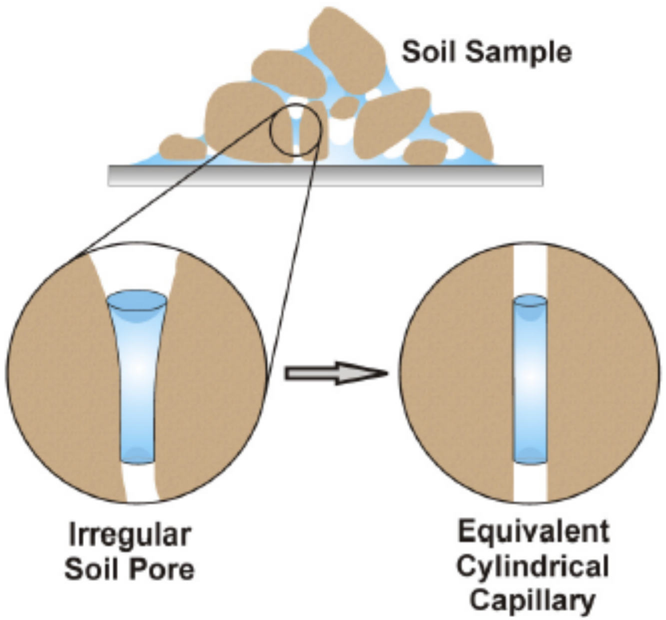
Dynamic permeability => inertial terms in Navier-Stokes for the water flow

Petrophysical developments for seismoelectrics

Effect of the frequency on water velocity in a pore

Let's consider pores as equivalent cylindrical capillaries

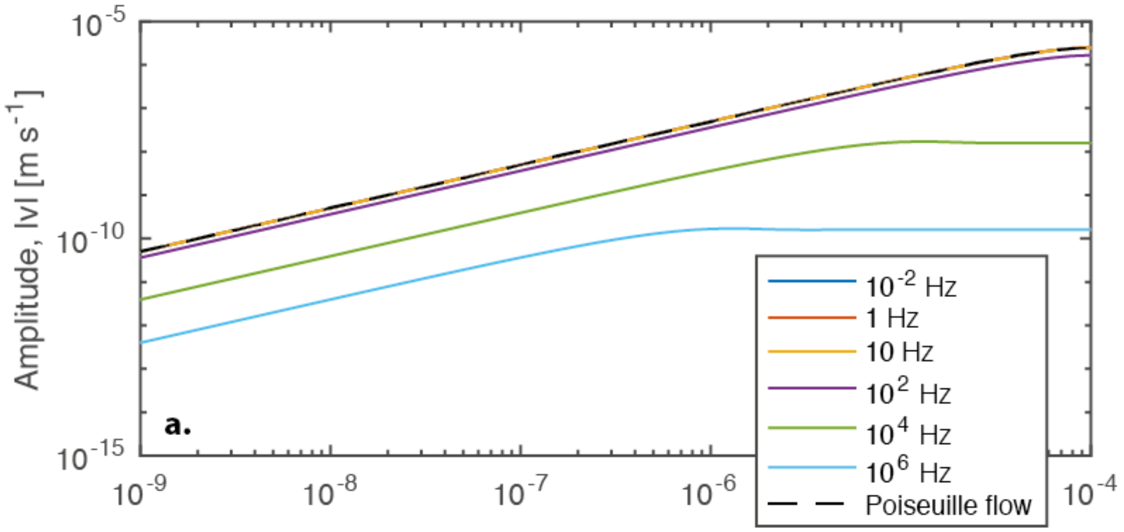
Analytical solution to Navier-Stokes equation for an oscillatory flow in the pore:



Or et al. (2009)

Distribution of water velocity in the pore:

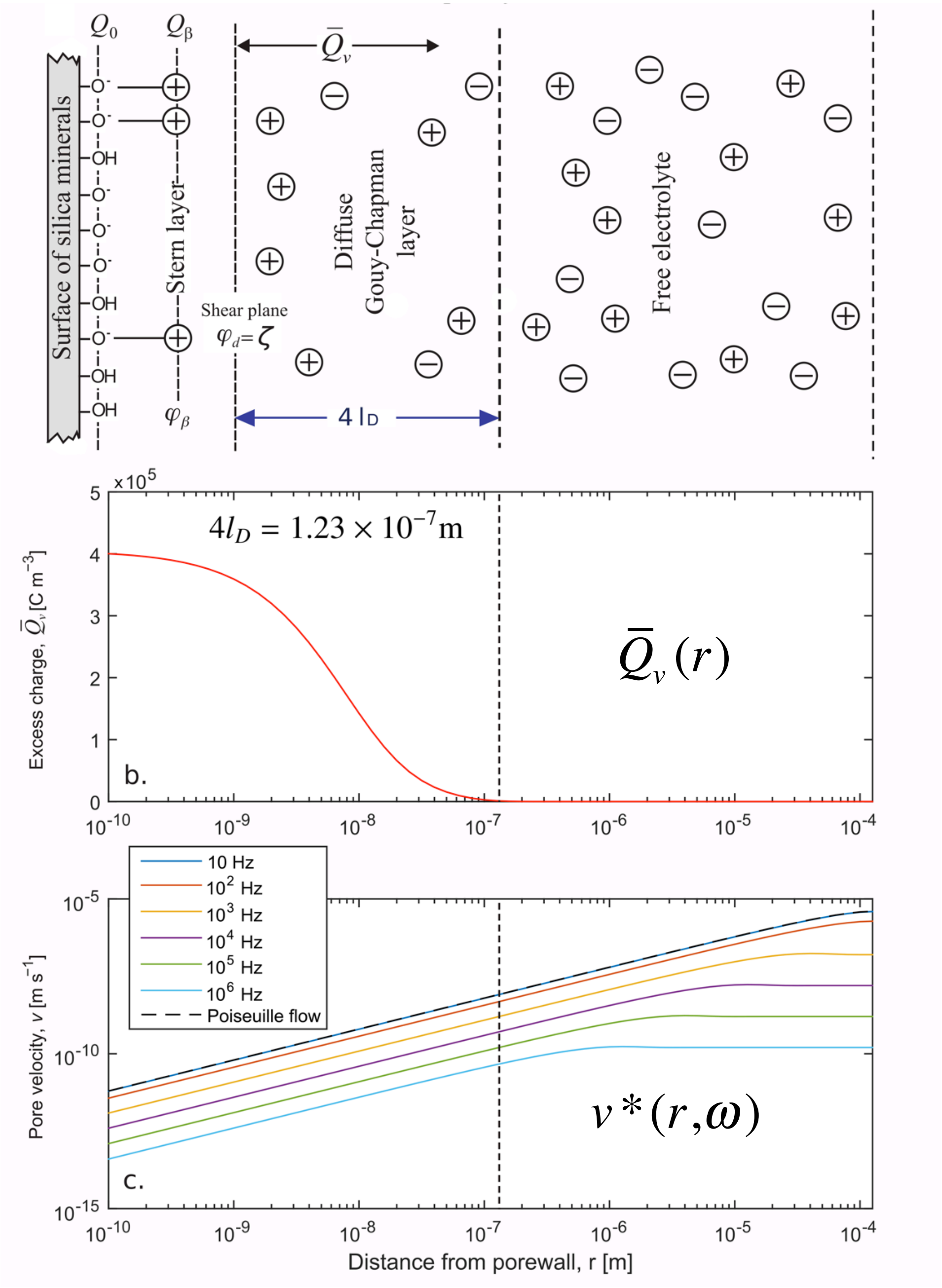
$$v^*(r,\omega) = \frac{1}{\eta_w \kappa^2}\left(\frac{J_0\left(\kappa(R-r)\right)}{J_0\left(\kappa R\right)} - 1\right)\frac{\Delta P(\omega)}{l}$$



Distance from pore wall [m]

Need for accurate dynamic permeability model

Description at the pore scale



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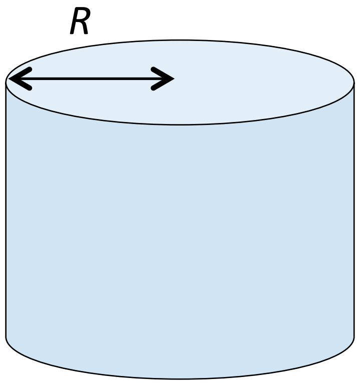


Frequency dependent water velocity

Description of the water velocity distribution in the pore

Frequency dependent effective excess charge

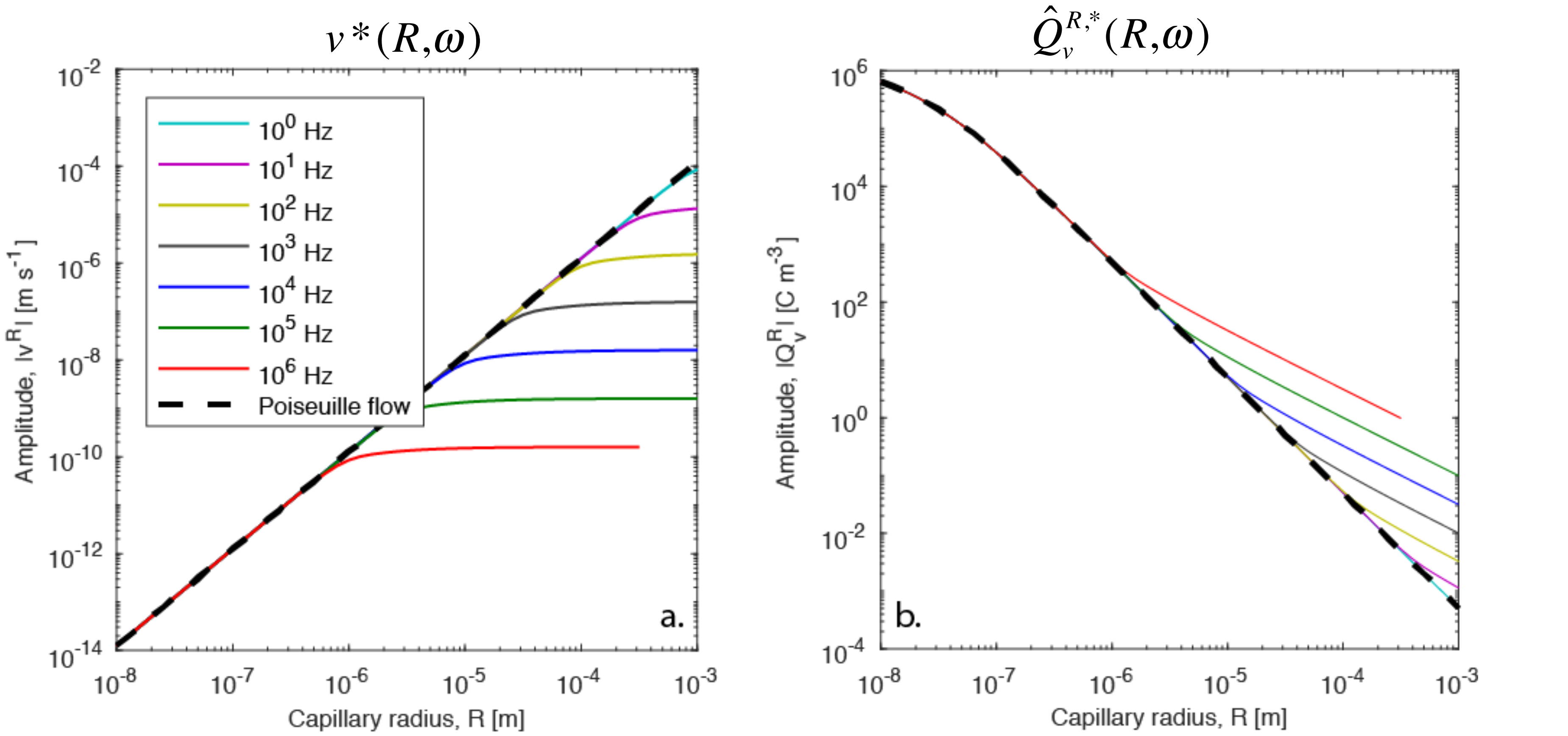
$$\hat{Q}_v^{R,*}(R,\omega) = \frac{\int_{r=0}^{R} \bar{Q}_v(r) v^*(r,\omega) r\,dr}{\int_{r=0}^{R} v^*(r,\omega) r\,dr}$$

We obtain the frequency dependent effective excess charge density for a given pore radius

Description at the pore scale

Frequency dependent effective excess charge at the pore scale

Evolution of water velocity and effective excess charge density as a function of pore size



Very strong effect of the pore size

22

Description at the REV scale

Up-scaling framework (Jougnot, 2019)

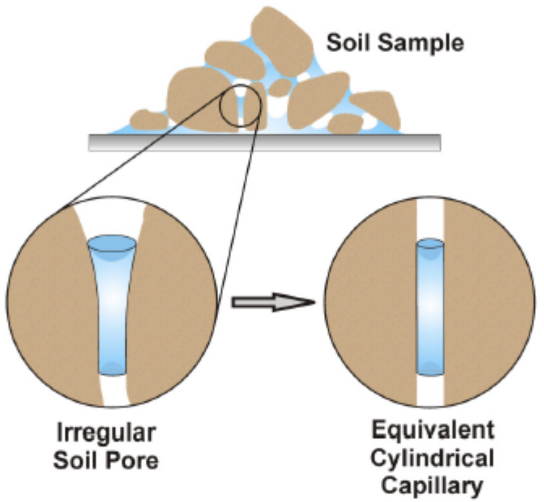
~ 1 – 10 nm — Description at the interface scale

↓ ← Pore shape and size

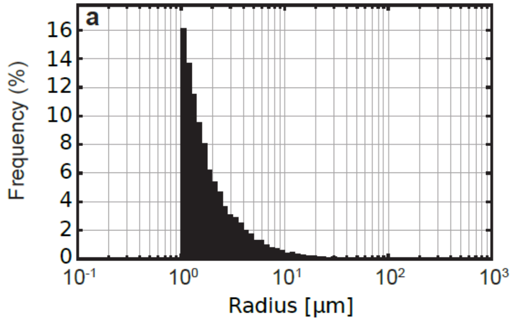
~ 10 nm – 1 mm — Description at the pore scale

↓ ← Pore size distribution

~ 1 cm – 1 m — Description at the REV scale



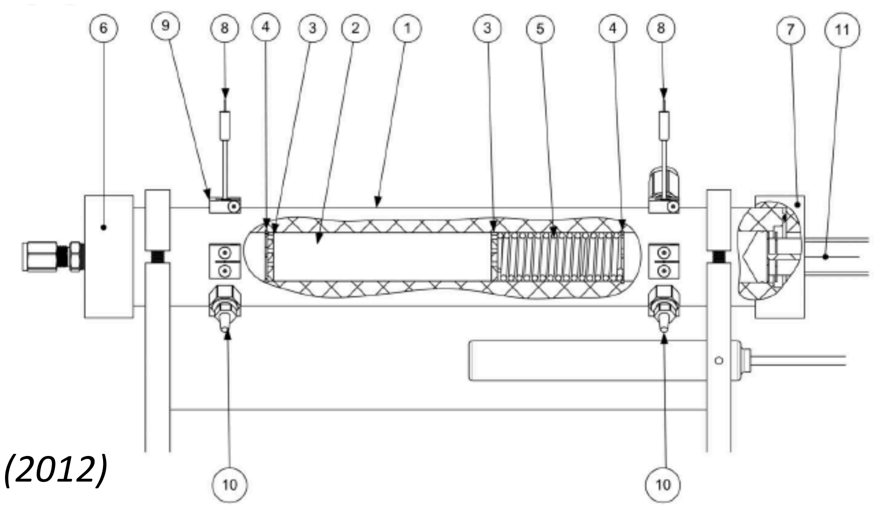
Or et al. (2009)



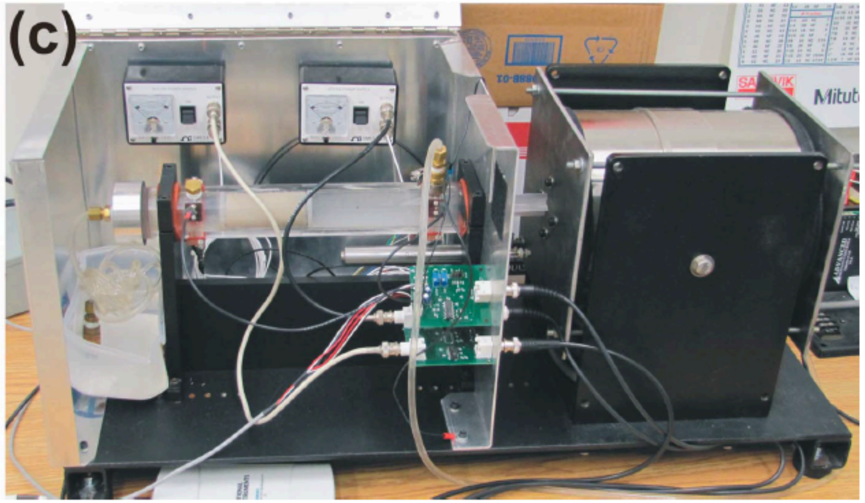
Jougnot et al. (2019)

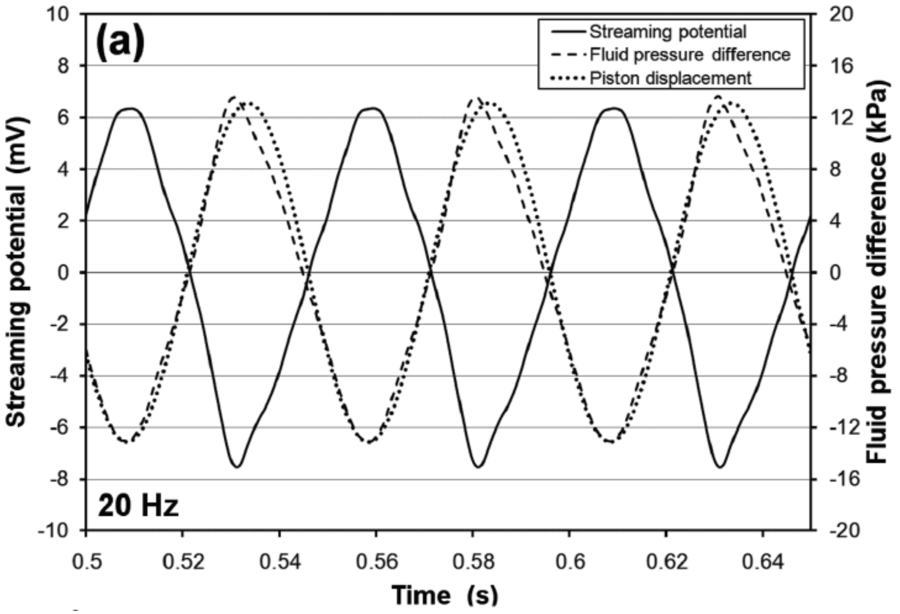
Description at the REV scale

Measurable parameter at the REV scale: the electrokinetic coupling coefficient (macroscopic parameter)



Tardiff et al. (2012)





Measuring the electrokinetic coupling coefficient (at different frequencies):

$$C^{EK} = \frac{\Delta\varphi(t)}{\Delta p_w(t)}$$

Frequency dependent electrokinetic coupling coefficient

Description at the REV scale

Relating the effective excess charge to a measurable parameter: the electrokinetic coupling coefficient

The electrokinetic coupling coefficient at the REV can be obtained from Revil and Mahardika (2013):

$$C_{EK}^{*}(\omega) = -\frac{\hat{Q}_v^{REV,*}(\omega)k^{*}(\omega)}{\eta_w \sigma^{*}(\omega)}$$

Dynamic parameters with respect to quasi-static values (f = 0 Hz)

$$k^{*}(\omega) = k^{0} k^{rel,*}(\omega)$$

$$\hat{Q}_v^{\mathrm{REV},*}(\omega) = \hat{Q}_v^{0} \hat{Q}_v^{rel,*}(\omega)$$

Let's consider that one pore size drives the response
(i.e. equivalent pore size assumption, see Packard 1953; Reppert et al. 2001)

Quasi-static parameters (0 Hz)

k^{0} can be measured

$\hat{Q}_v^{0}$ can be measured or obtained from the analytical solution of Guarracino and Jougnot (2018)

Relative dynamic parameters (numerical model)

$$k^{rel,*}(\omega) = \frac{v^{R,*}(\omega)}{v^{R,*}(\omega = 0)}$$

$$\hat{Q}_v^{rel,*}(\omega) = \frac{\hat{Q}_v^{R,*}(\omega)}{\hat{Q}_v^{R,*}(\omega = 0)}$$

Obviously a very strong effect of the pore size

Description at the REV scale

From the effective excess charge to the electrokinetic coupling coefficient

$$k^*(\omega)$$

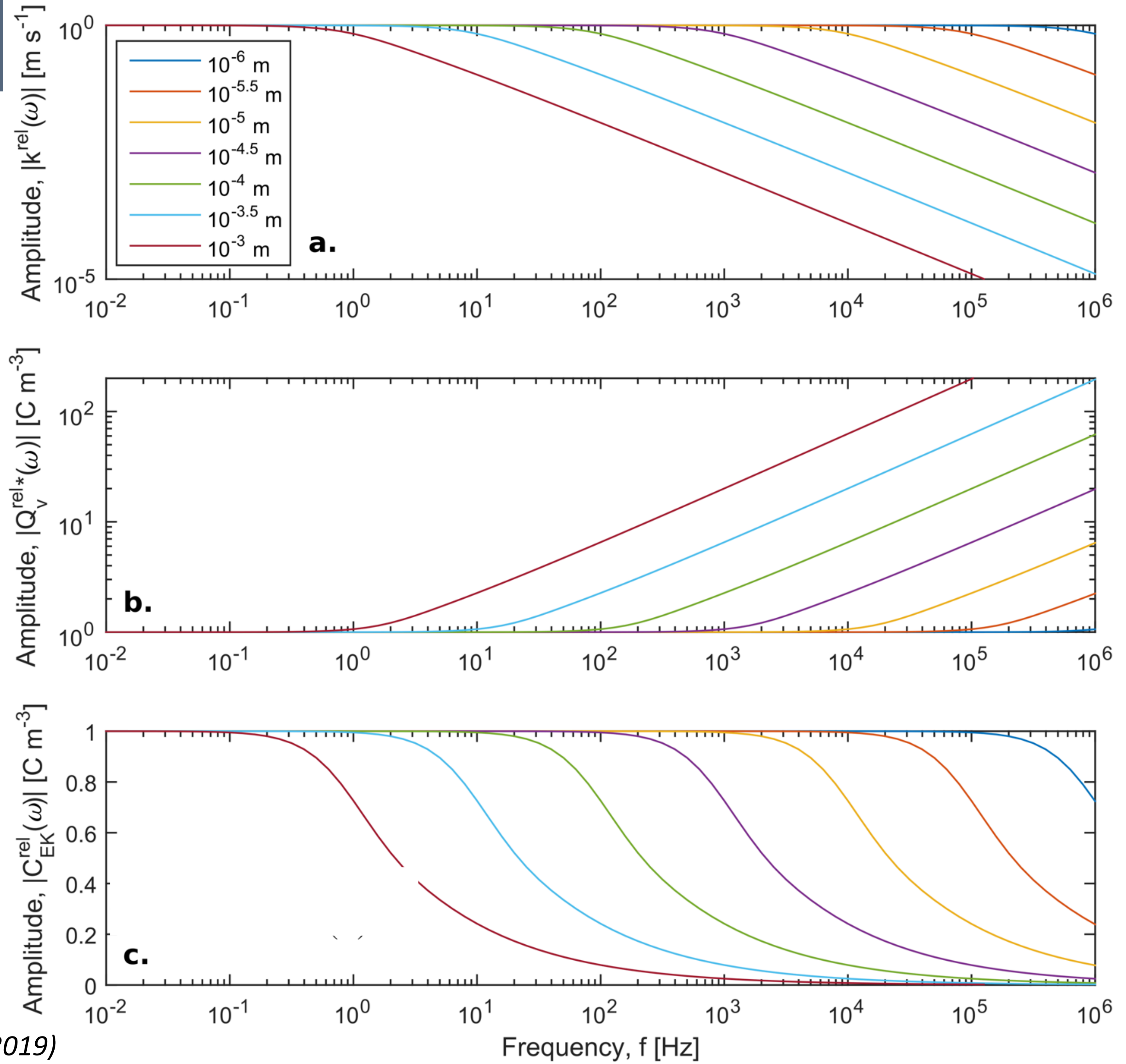
We consider equivalent pore size from 10^{-6} to 10^{-3} m

$$\hat{Q}_v^{\mathrm{REV},*}(\omega)$$

Frequency behavior consistent with literature data

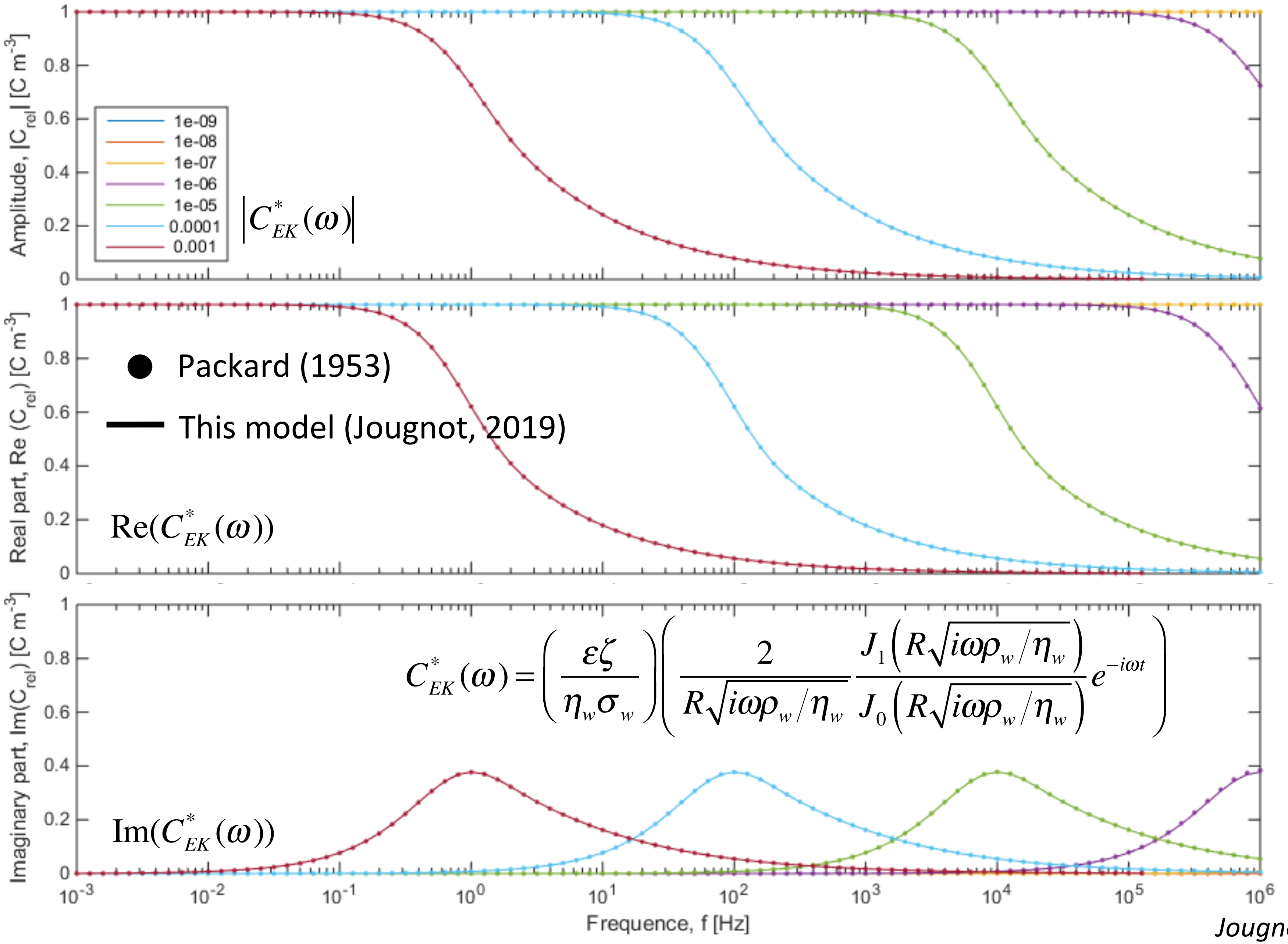
$$C_{EK}^*(\omega) = -\frac{\hat{Q}_v^{REV,*}(\omega)k^*(\omega)}{\eta_w \sigma^*(\omega)}$$

(e.g. Pengra et al. 1999, Tardiff et al. 2012, Zhu and Toksöv 2012)



Jougnot (2019)

Description at the REV scale – comparison with existing model



Packard (1953) proposes an analytical solution for a given capillary

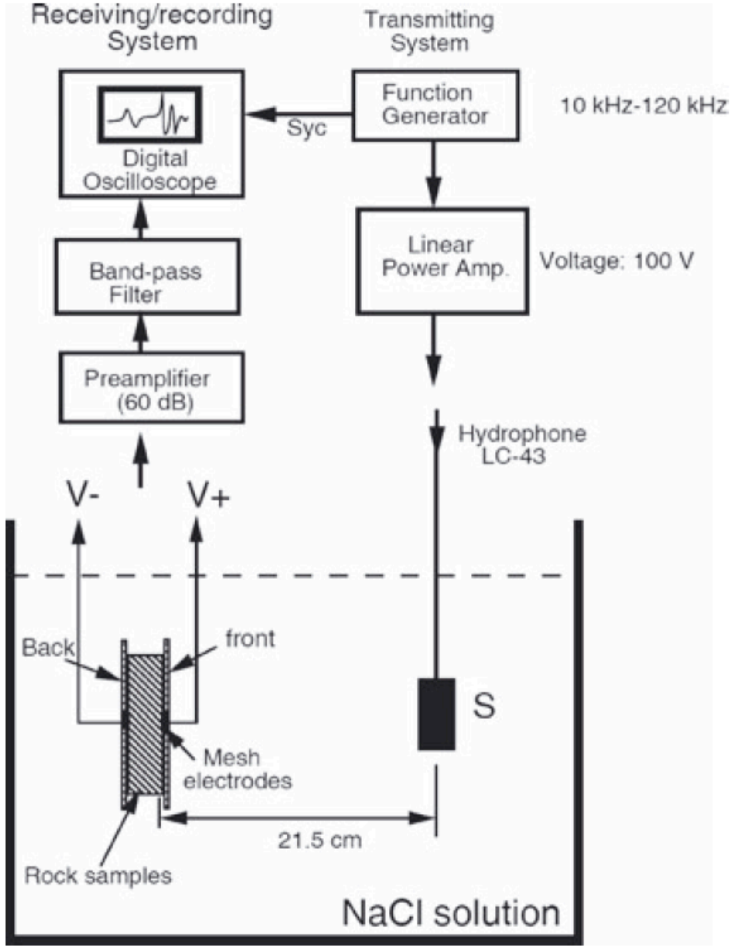
We compare the models for equivalent pore size from 10^{-9} to 10^{-3} m

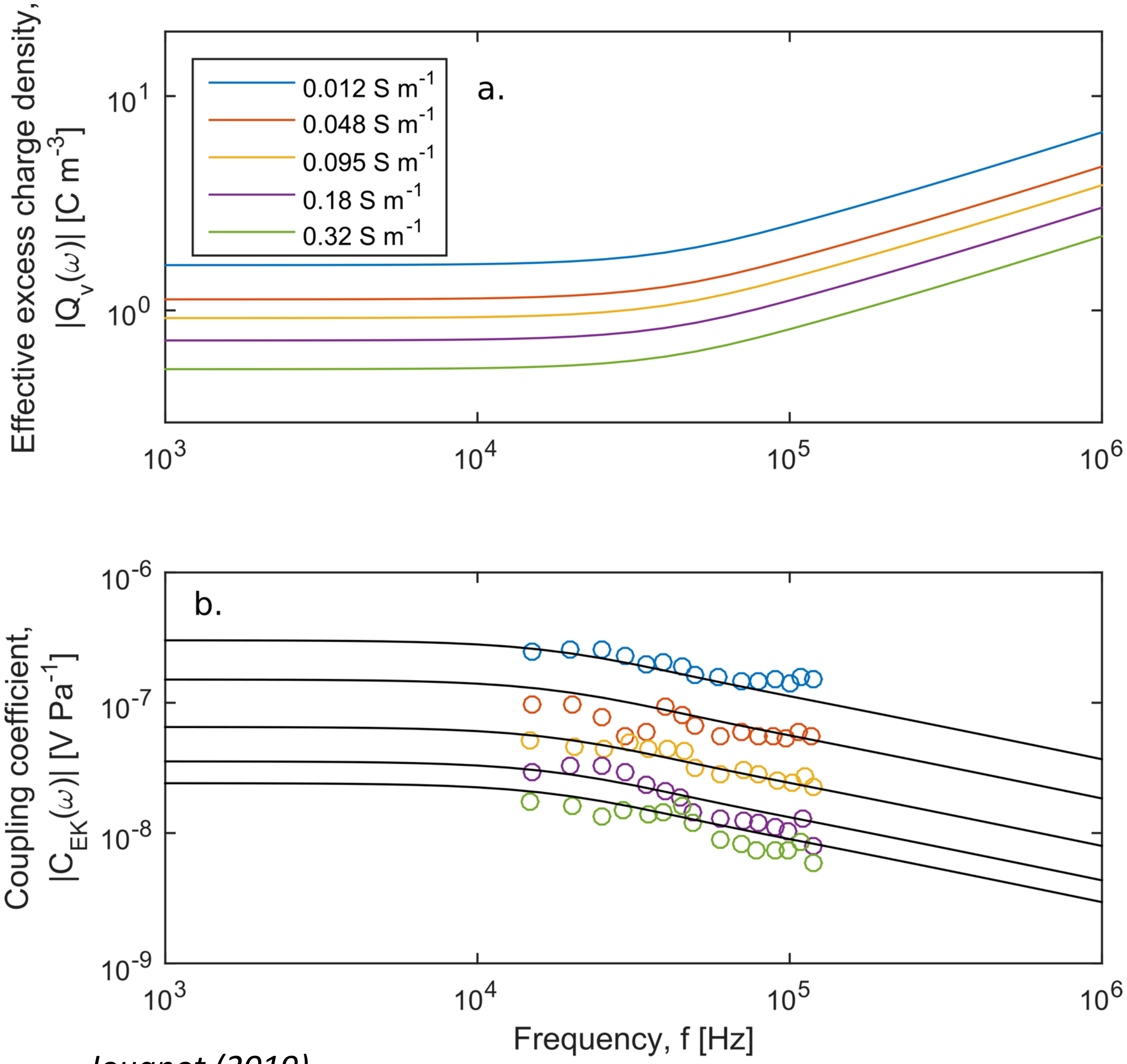
The model of Jougnot (2019) perfectly reproduces the complex coupling coefficient (amplitude, real and imaginary part) using a different approach

Jougnot (2019)

Description at the REV scale – comparison with water saturated data

Electrokinetic coupling coefficient of a Berea sandstone at various salinity and various frequencies (Zhu and Toksöv 2012)





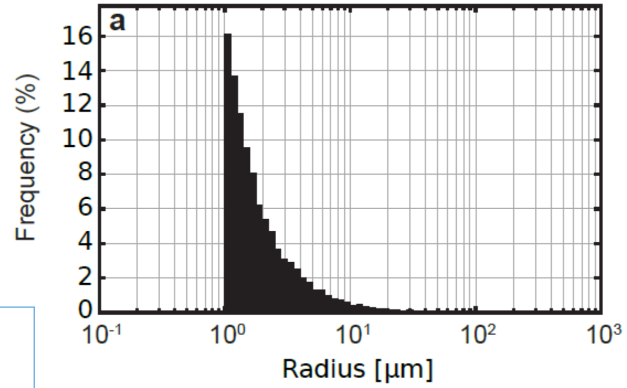
Jougnot (2019)

Safistfying results for water saturated porous medium

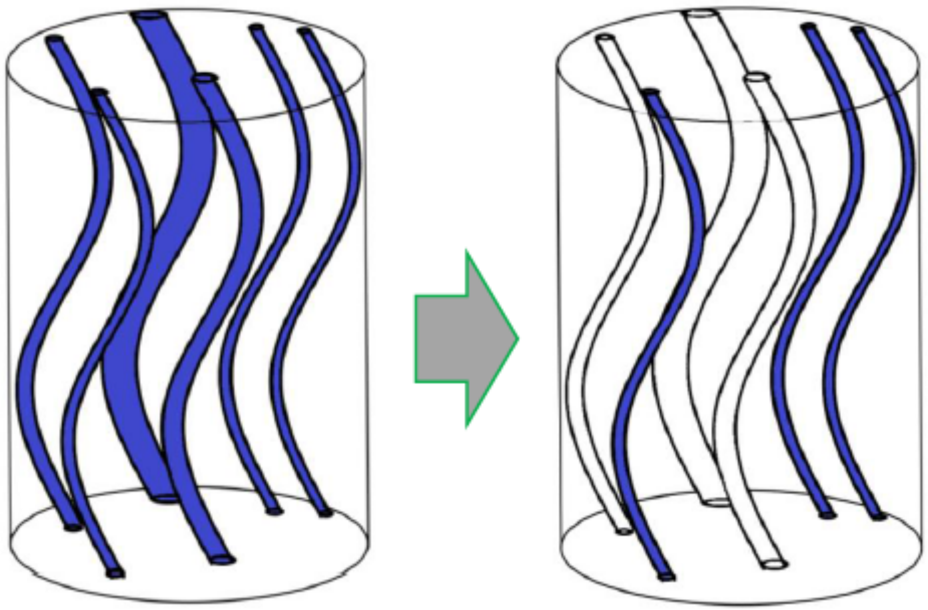
Description at the REV scale –partially saturated medium

Effective excess charge and electrokinetic coupling coefficient under partially saturated conditions

- The REV is a bundle of capillaries which sizes follow a fractal distribution
- a given capillary is either water saturated either dry (larger dry first)
- An analytical solution is obtained for the effective excess charge and coupling coefficient



Jougnot et al. (2019)



Drainage (S_w ↘)

Soldi et al. (2019)

$$\hat{Q}_v^{\mathrm{REV,rel}}(S_w) = \hat{Q}_v^{\mathrm{REV,sat}} \frac{S_e}{k^{\mathrm{rel}}(S_e)}$$

$$C_{\mathrm{EK}}(S_{\mathrm{w}}) = C_{\mathrm{EK}}^{sat} \frac{\hat{Q}_v^{\mathrm{REV,rel}}(S_w) k^{\mathrm{rel}}(S_w)}{\sigma^{rel}(S_w)}$$

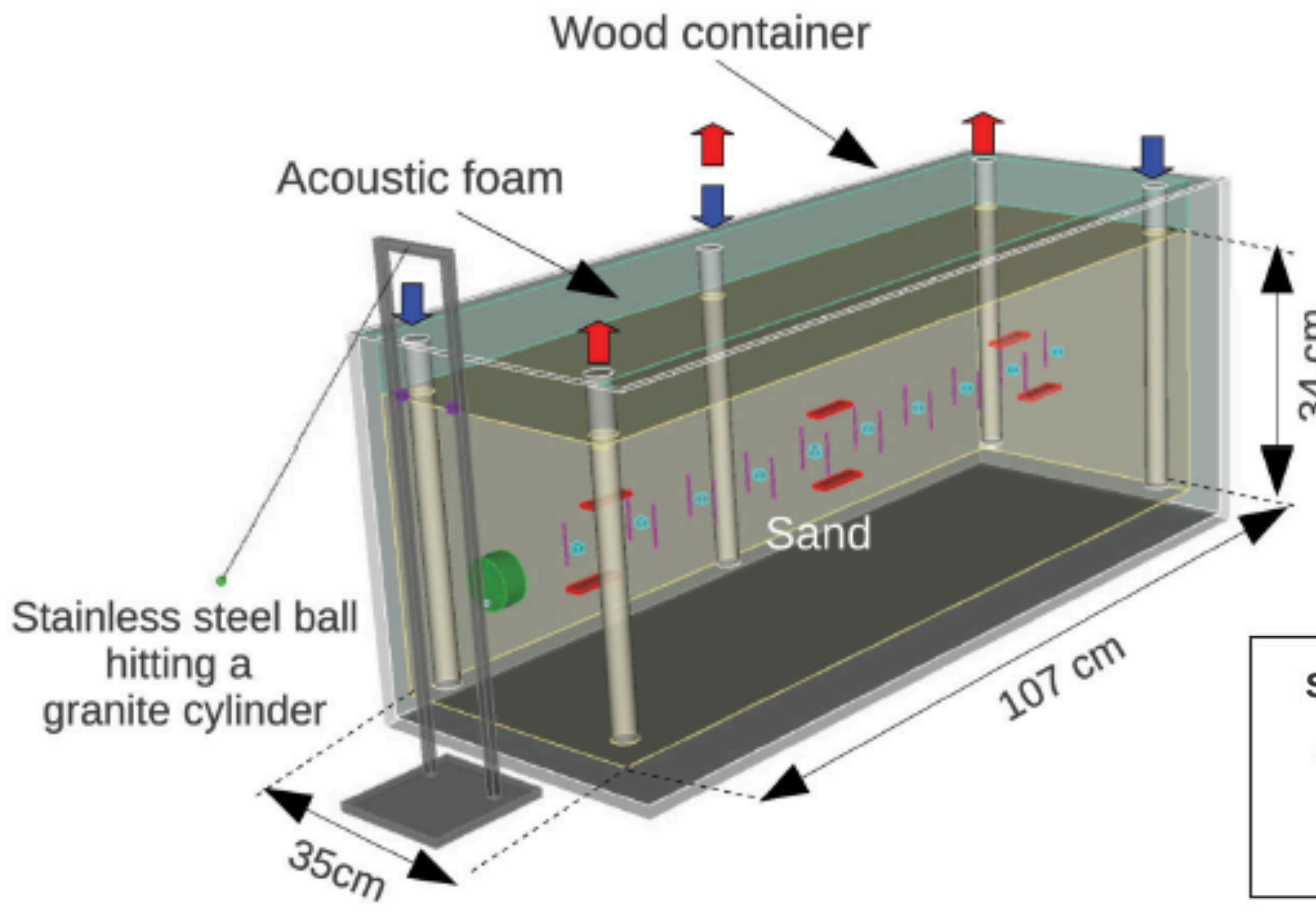
$$C_{\mathrm{EK}}(S_{\mathrm{w}}) = C_{\mathrm{EK}}^{sat} \frac{S_e}{\sigma^{rel}(S_w)}$$

S_e = effective saturation
σ^{rel} = relative electrical conductivity

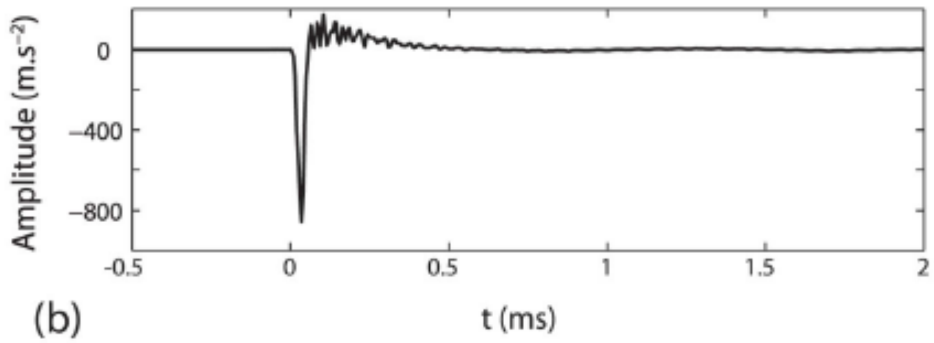
A rather simple analytical solution for the electrokinetic coupling coefficient under partial saturation

Description at the REV scale – comparison with partially saturated data

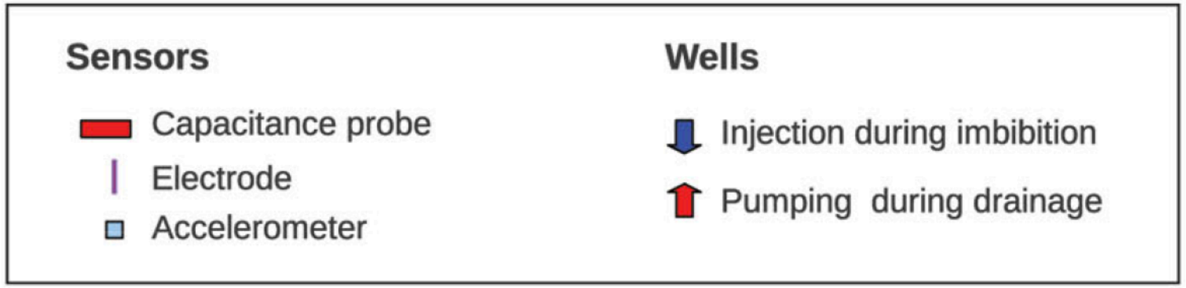
Seismoelectric monitoring drainage and imbibition of a sand filled tank



Seismic sources



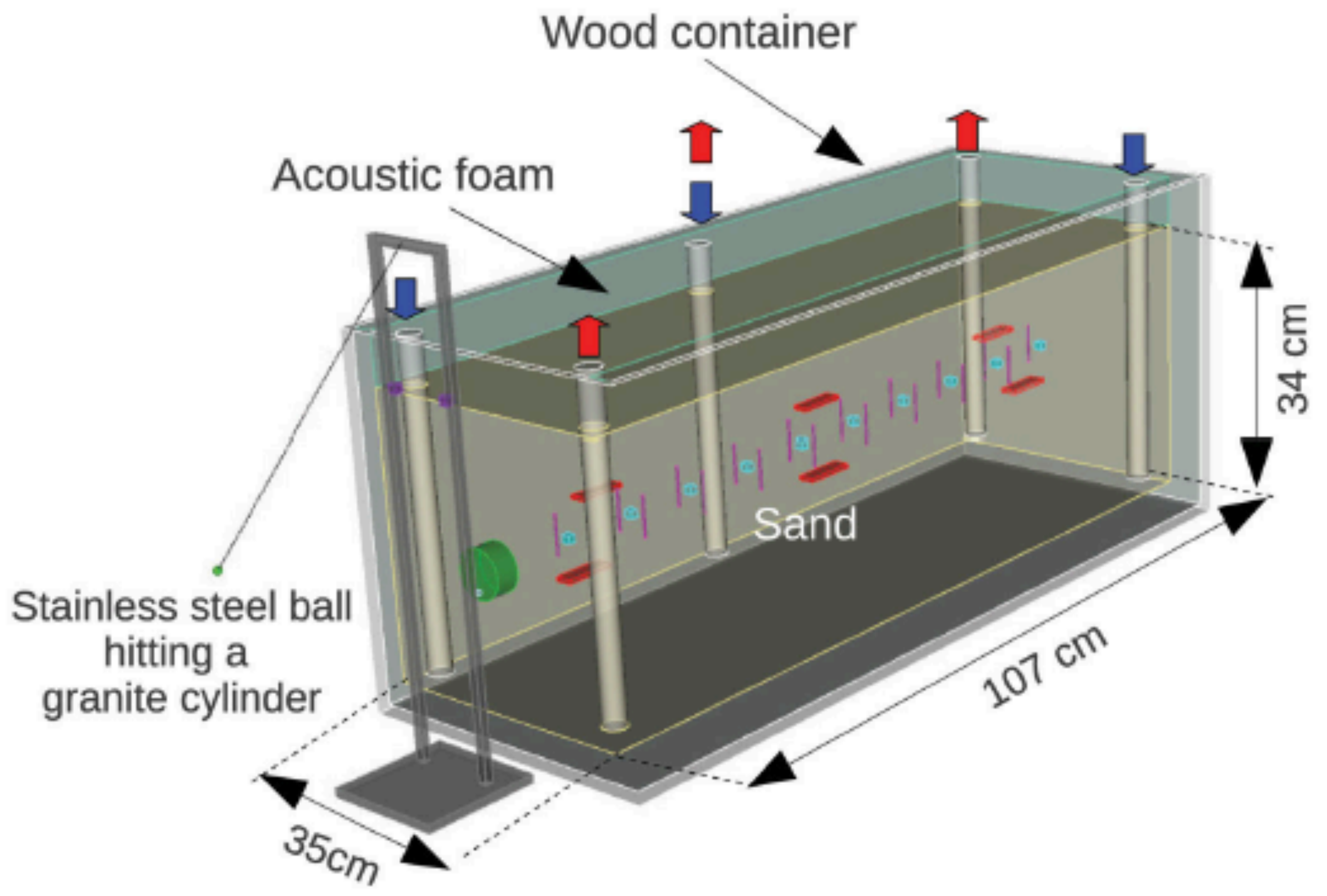
Seismic and electrical monitoring



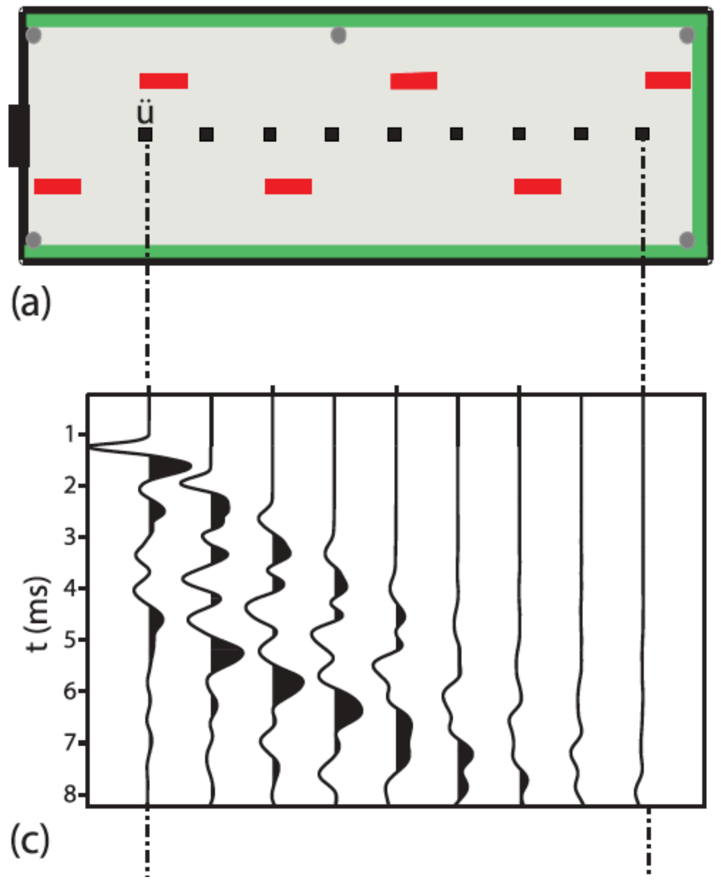
Bordes et al. (2015)

Description at the REV scale – comparison with partially saturated data

Seismoelectric monitoring drainage and imbibition of a sand filled tank



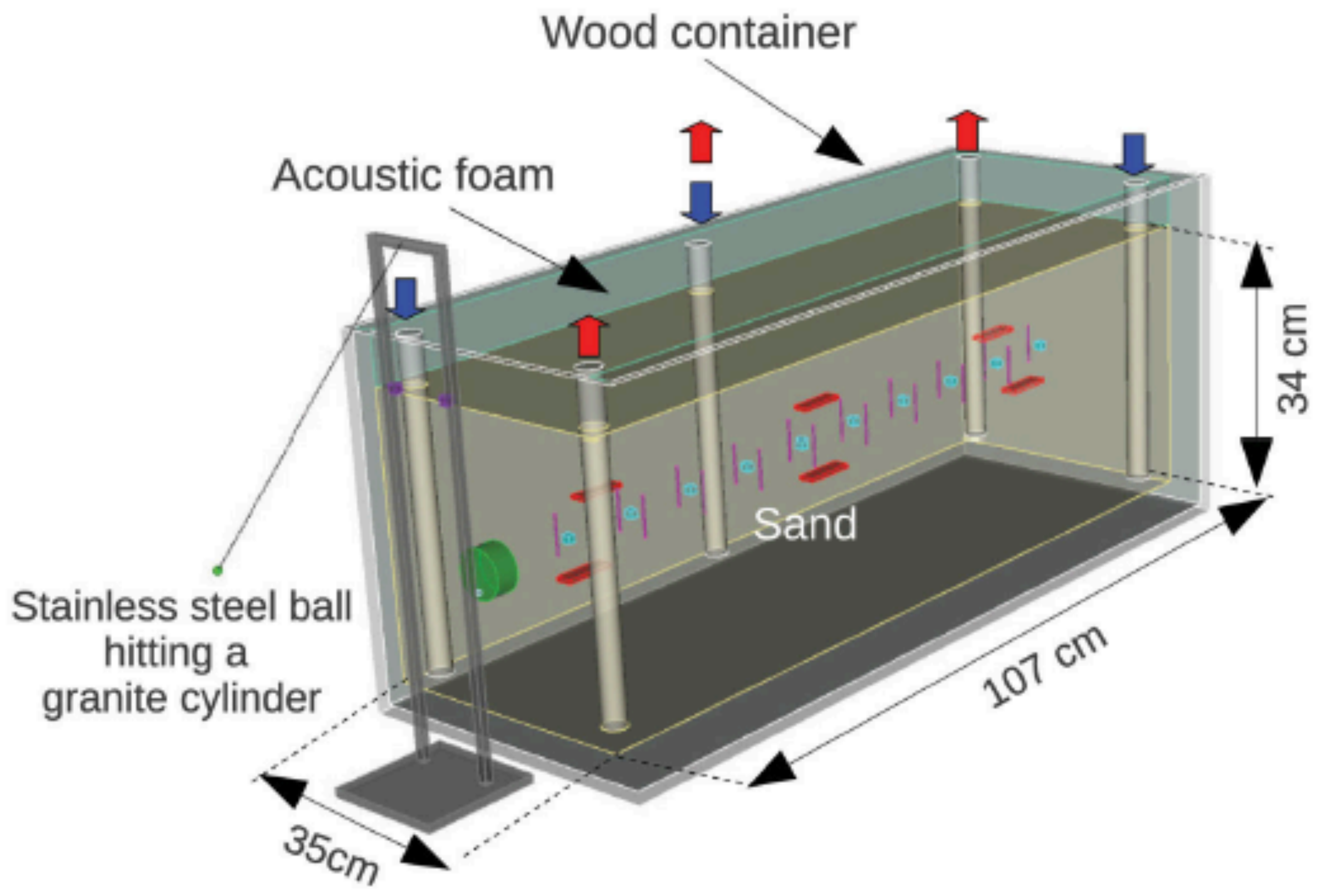
Seismic records at various offsets



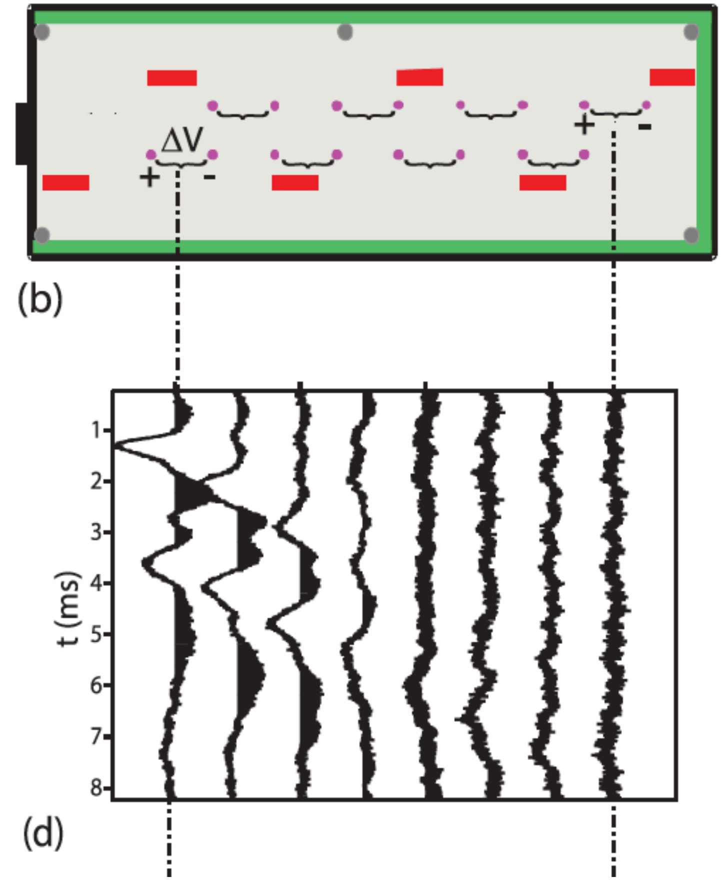
Bordes et al. (2015)

Description at the REV scale – comparison with partially saturated data

Seismoelectric monitoring drainage and imbibition of a sand filled tank



Seismoelectric records at various offsets

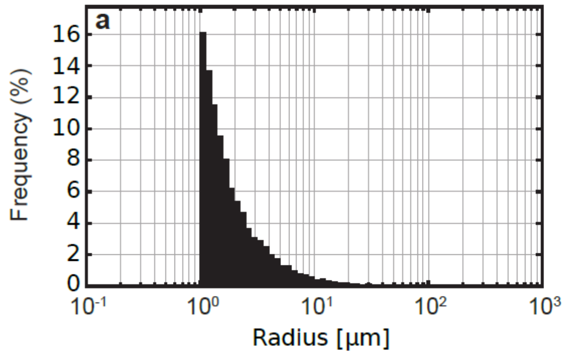


Bordes et al. (2015)

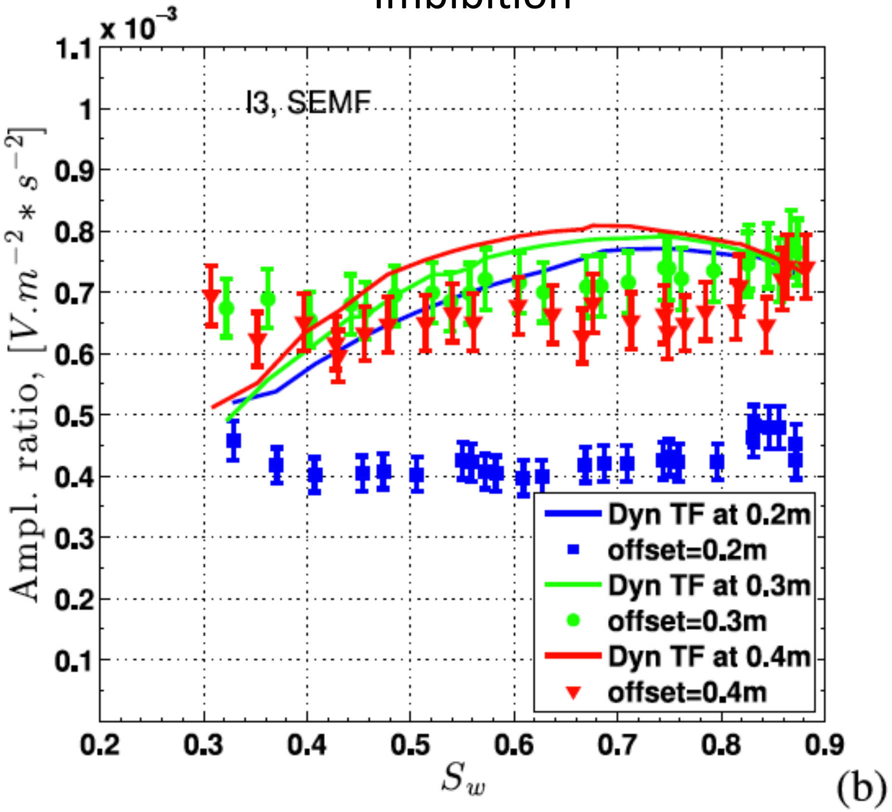
Description at the REV scale – comparison with partially saturated data

Modeling the amplitude ratio of the transfer function (depending on coupling coefficient)

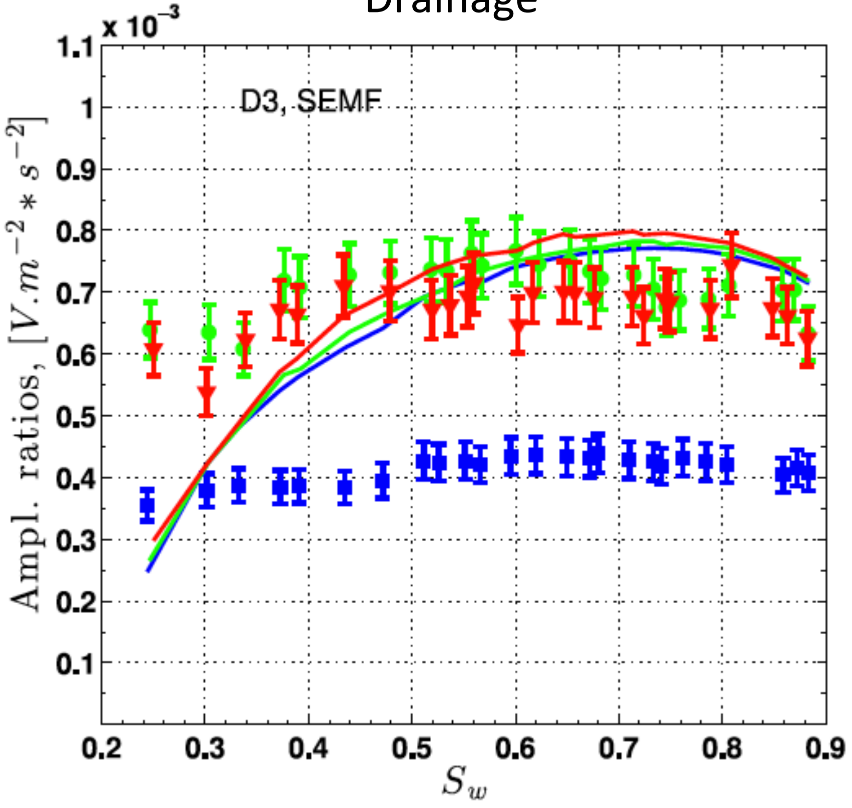
- 1D approximation
- analytical model based on fractal pore size distribution (Jackson 2010, Soldi et al. 2019)



Imbibition



Drainage



OK, but could be improved, especially at low saturation…

Jougnot et al. (2012) showed the importance of pore size distribution at low saturation

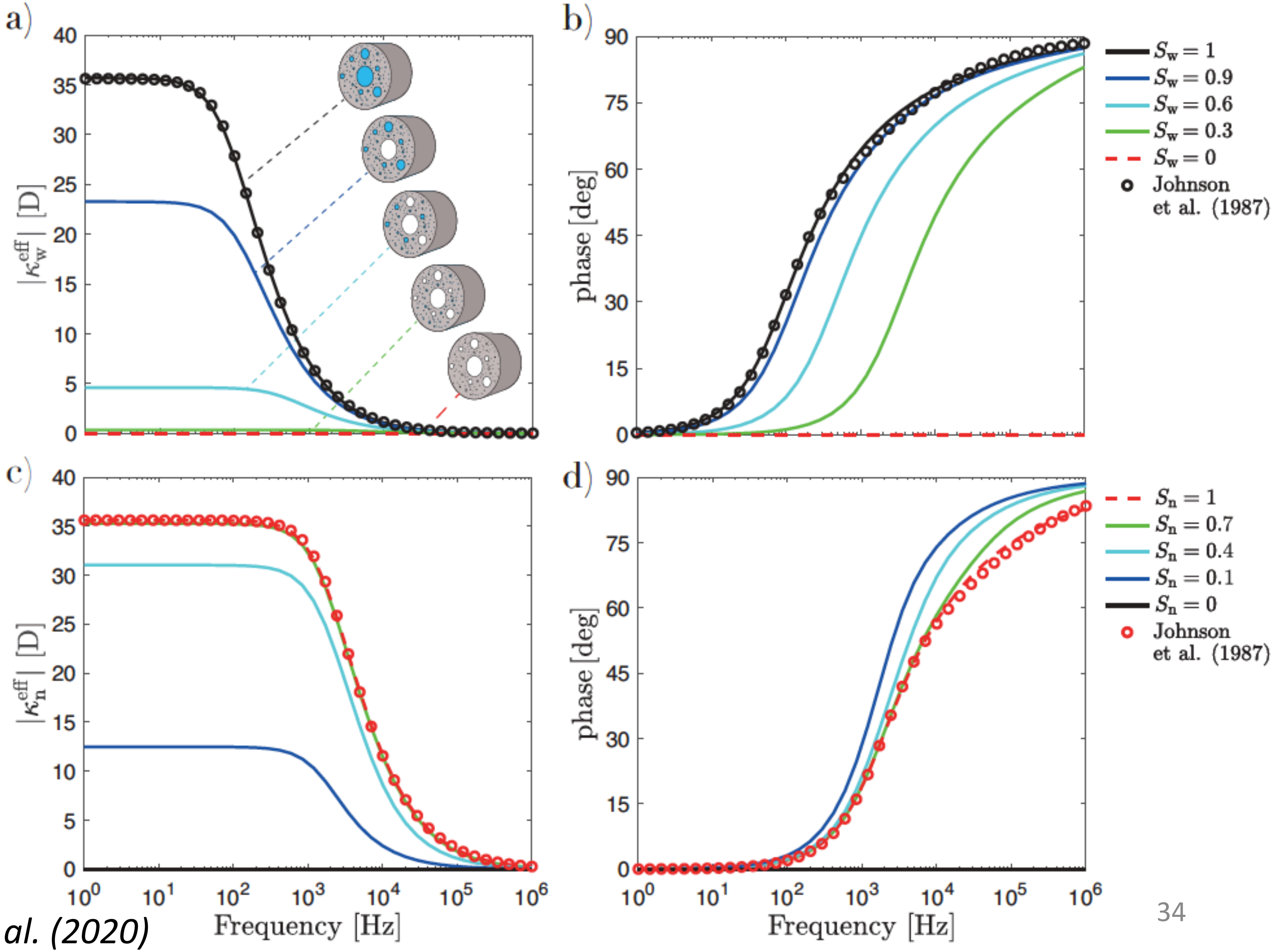
Bordes et al. (2015)

Next step: improving the dependence to the water saturation…

Description at the REV scale – next steps…

Solazzi et al. (2020) propose a simple way to model the dynamic permeability of partially saturated media

- REV is a capillary bundle
- Pore size distribution is user-defined
- Approach validated with the model of Johnson et al. (1987) for saturated conditions (with wetting and non wetting fluid)
- We see that the equivalent capillary changes with saturation



Next step:

➔ Implement Solazzi et al. (2020) model for dynamic permeability in the upscaling framework presented by Jougnot (2019)

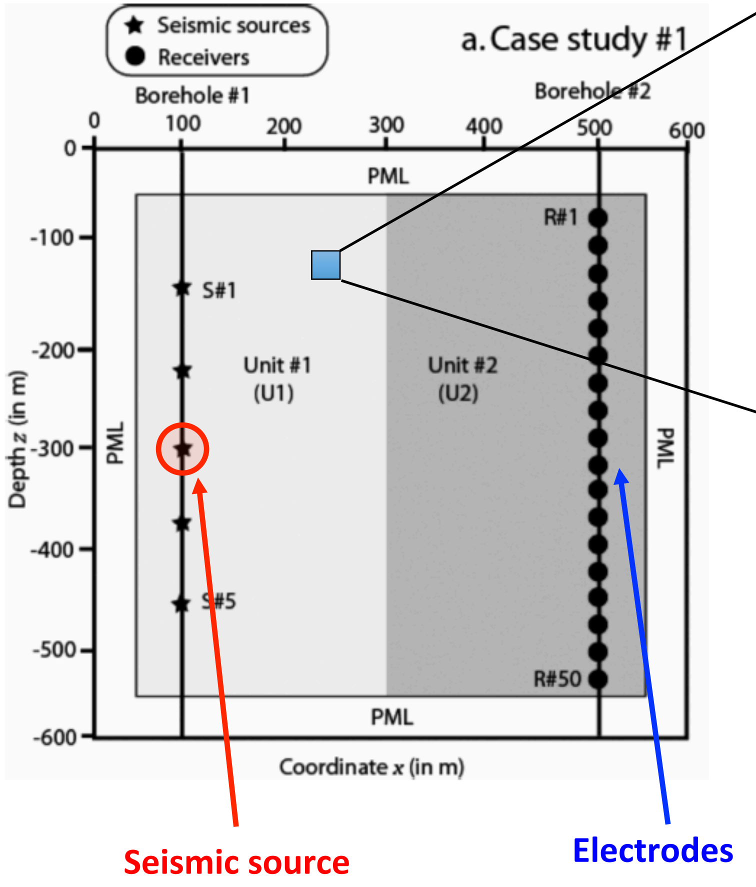
➔ Use the resulting code as a petrophysical brick in a fully coupled seismoelectric modelling

Solazzi et al. (2020)

Seismoelectrical modelling – next steps…

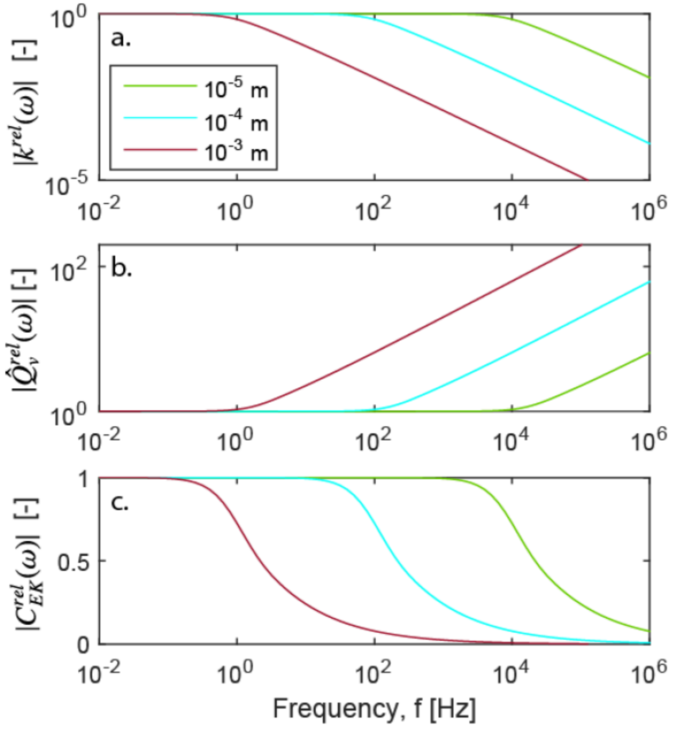
➔ Use the resulting code as a petrophysical brick in a fully coupled seismoelectric numerical simulation

e.g., back to the exemple of Araji et al. (2012) cross-brohole study



Each cell of the numerical simulation, described by:

- porosity
- dynamic permeability
- water saturation
- electrical conductivity
- mechanical properties (bulk & shear modulii)
- effective excess charge
- coupling coefficient
- …



➔ To obtain a fully mechanistically coupled seismoelectrical forward model for porous media saturated by two fluids:

- reservoir characterization (oil, gas, CO2, H, …)
- near surface (contaminated) area
- …

Conclusions & perspectives

What we have :

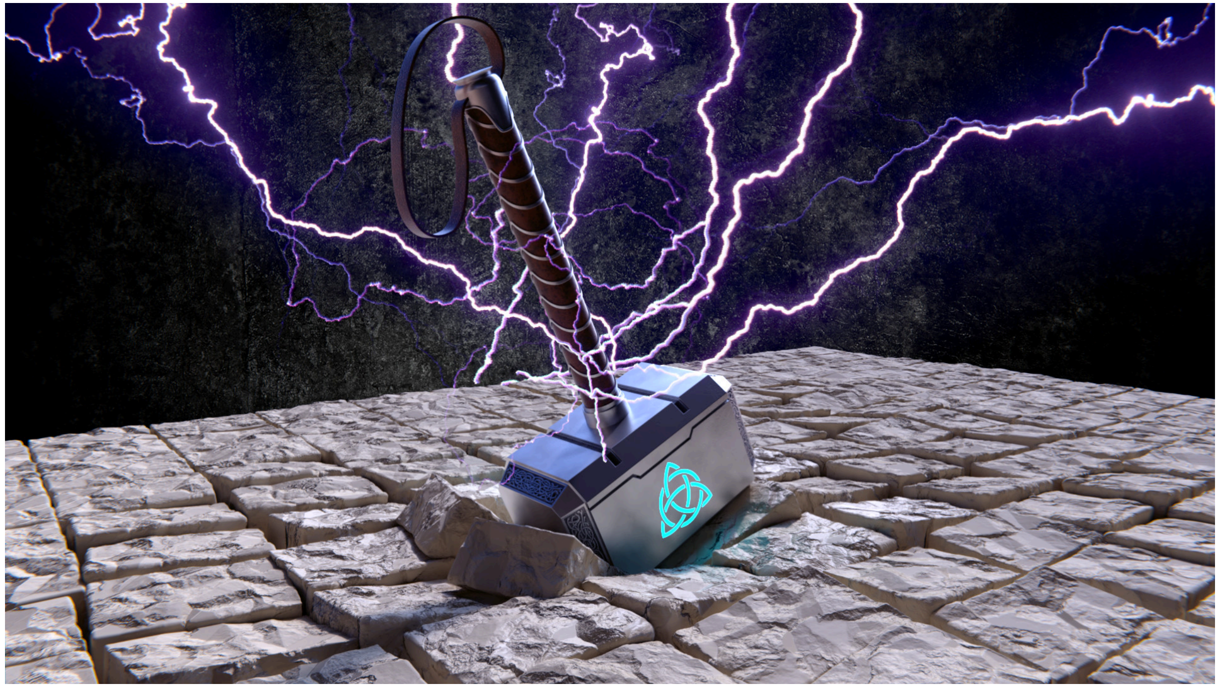
- Seismoelectric method combines interest from seismic and electrical methods
- Signals related to properties of interest for reservoir or contaminated area characterization
- Good petrophysical model (frequency dependent EK coupling) is needed to quantitatively exploit the signals
- Up-scaling approach validated in saturated conditions (match experimental data)
- Decent match with experiment for partially saturated conditions

What we need :

- Extend the model for partial saturation
- Implement the model in a larger framework for seismoelectric modeling

Thank you for your (virtual) attention…

…any questions ?



Credits: Ravi Verma

Do not hesitate to visit:

https://sites.google.com/site/damienjougnot/

@DamienJougnot

@SanSolazzi

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