Innovations, Challenges, and Future Opportunities

J. Carlos Santamarina
Georgia Institute of Technology

electromagnetic waves

Maxwell's Equations

Gauss' Law of Electricity	$\int_{surf} \varepsilon \mathbf{E} \cdot d\mathbf{s} = \int_{vol} \rho_v^{\langle\text{free}\rangle} dv$	$\nabla \cdot \mathbf{E} = \frac{1}{\varepsilon} \rho_v^{\langle\text{free}\rangle}$
Gauss' Law of Magnetism	$\int_{surf} \mathrm{H} \cdot d\mathbf{s} = 0$	$\nabla \cdot \mathbf{H} = 0$
Faraday's Law of Induction	$\int_{loop} \mathrm{E} \cdot d\mathbf{l} = -\frac{d}{dt} \int_{surf} \mu \mathrm{H} \cdot d\mathbf{s}$	$\nabla \times \mathbf{E} = -\mu \frac{d\mathbf{H}}{dt}$
Ampere-Maxwell's Law	$\int_{loop} \mathbf{H} \cdot d\mathbf{l} = \int_{surf} \mathbf{J} \cdot d\mathbf{s} + \frac{d}{dt} \int_{surf} \varepsilon \mathbf{E} \cdot d\mathbf{s}$	$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \varepsilon \frac{d\mathbf{E}}{dt}$

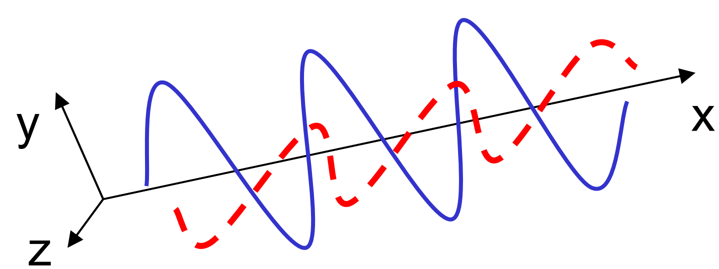
Wave Equation

$$\nabla^2 E = \mu^* \sigma \frac{\partial E}{\partial t} + \mu^* \varepsilon^* \frac{\partial^2 E}{\partial t^2}$$

Solution: $E_y = E_o e^{-\alpha x} e^{j(\omega t - \kappa x)} = E_o e^{j(\omega t - \gamma^* x)}$

Then $\gamma^* = \alpha + j\kappa = \sqrt{j\omega\sigma\mu^* - \omega^2 \varepsilon^* \mu^*}$

Faraday: $H_z = -j \frac{\gamma^*}{\mu\omega} E_y$



Phase Velocity

$$V_{ph} = \frac{\omega}{\mathrm{Im}\,(\gamma^*)} = \frac{\omega}{\mathrm{Im}\left(\sqrt{j\omega\sigma\mu^* - \omega^2\varepsilon^*\mu^*}\right)}$$

non-ferromagnetic / dielectric

$\mu^* = \mu_o \qquad \varepsilon^* = \varepsilon' \qquad \sigma = 0$

$$V_{ph} = \frac{c_o}{\sqrt{\varepsilon'/\varepsilon_o}}$$

Attenuation

$$\alpha = \mathrm{Re}(\gamma^*) = \mathrm{Re}\left(\sqrt{j\omega\sigma\mu^* - \omega^2\varepsilon^*\mu^*}\right)$$

non-ferromagnetic

$\mu^* = \mu_o \qquad \varepsilon^* = \varepsilon' + j\varepsilon'' \qquad \sigma$

$$\alpha = \frac{\omega\sqrt{\varepsilon'/\varepsilon_o}}{c_o}\sqrt{\frac{1}{2}\left(\sqrt{1+\tan^2\delta} - 1\right)}$$

For 1D propagation

Skin depth

$$S_d = \frac{1}{\alpha} = \frac{1}{\mathrm{Re}(\gamma^*)}$$

Impedance

$$z^* = \frac{E_y}{H_z} = j\frac{\omega}{\gamma^*}\mu^*$$

Reflection and Transmission

$$R^* = \frac{1-\left(z_1^*/z_2^*\right)}{1+\left(z_1^*/z_2^*\right)} \qquad T^* = \frac{2}{1+\left(z_1^*/z_2^*\right)}$$

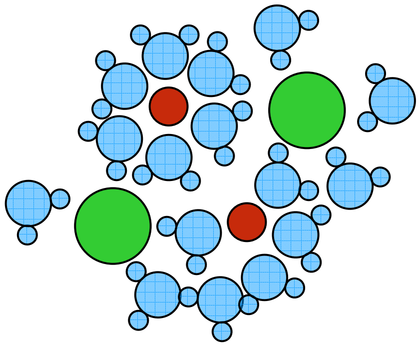
Electromagnetic Parameters

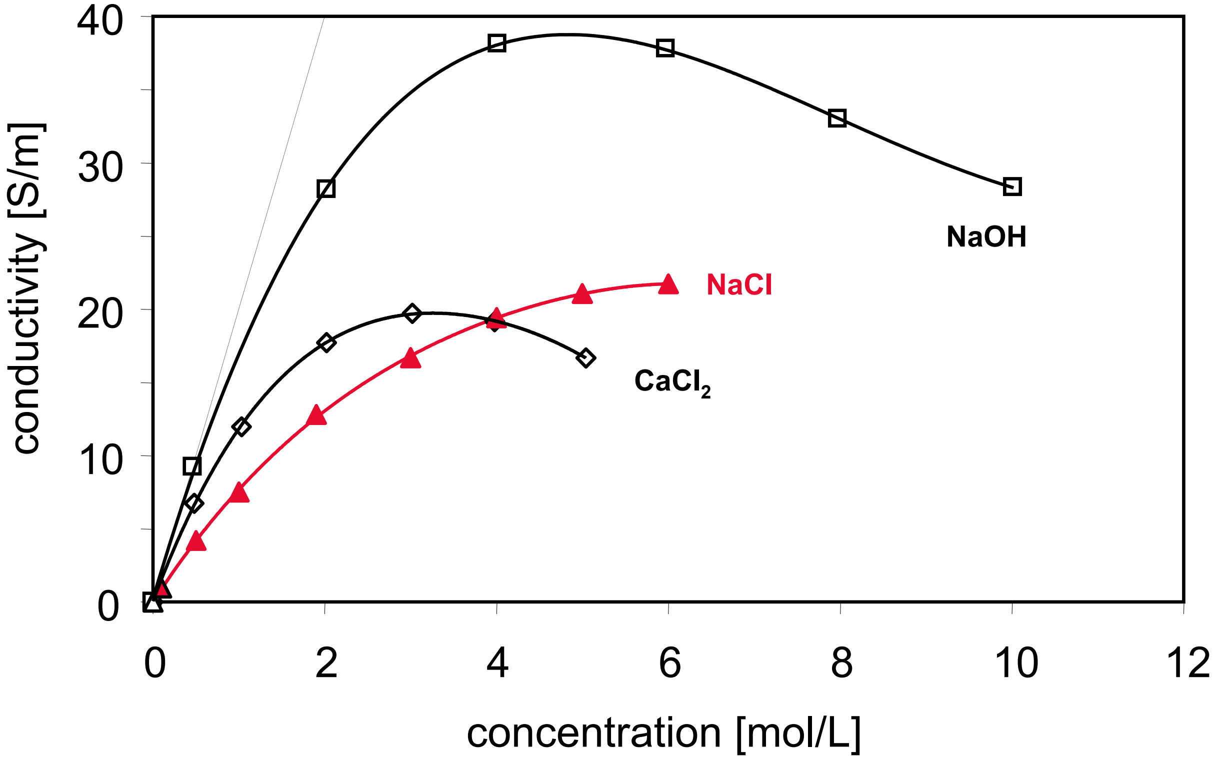
Conductivity	σ
Permittivity	$\varepsilon^* = \varepsilon' - j\,\varepsilon''$
Permeability	$\mu = \mu' - j\,\mu''$
Effective conductivity	$\sigma_{eff} = \varepsilon'\omega\,\mu_r'' + (\sigma + \varepsilon''\omega)\,\mu_r'$

details and references in
Santamarina, Klein and Fam
Soils and Waves – J. Wiley

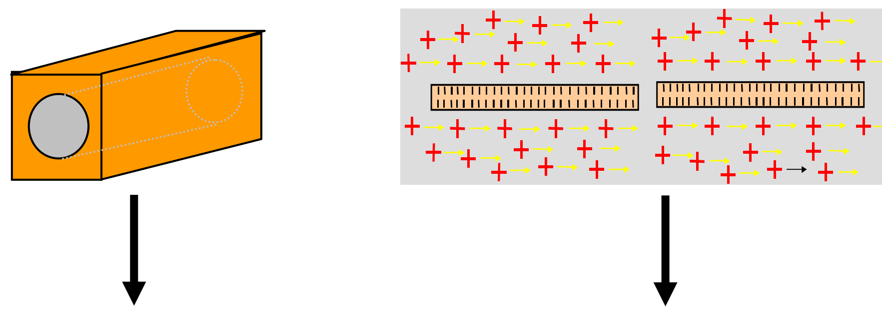
electromagnetic properties

Conductivity - Electrolytes





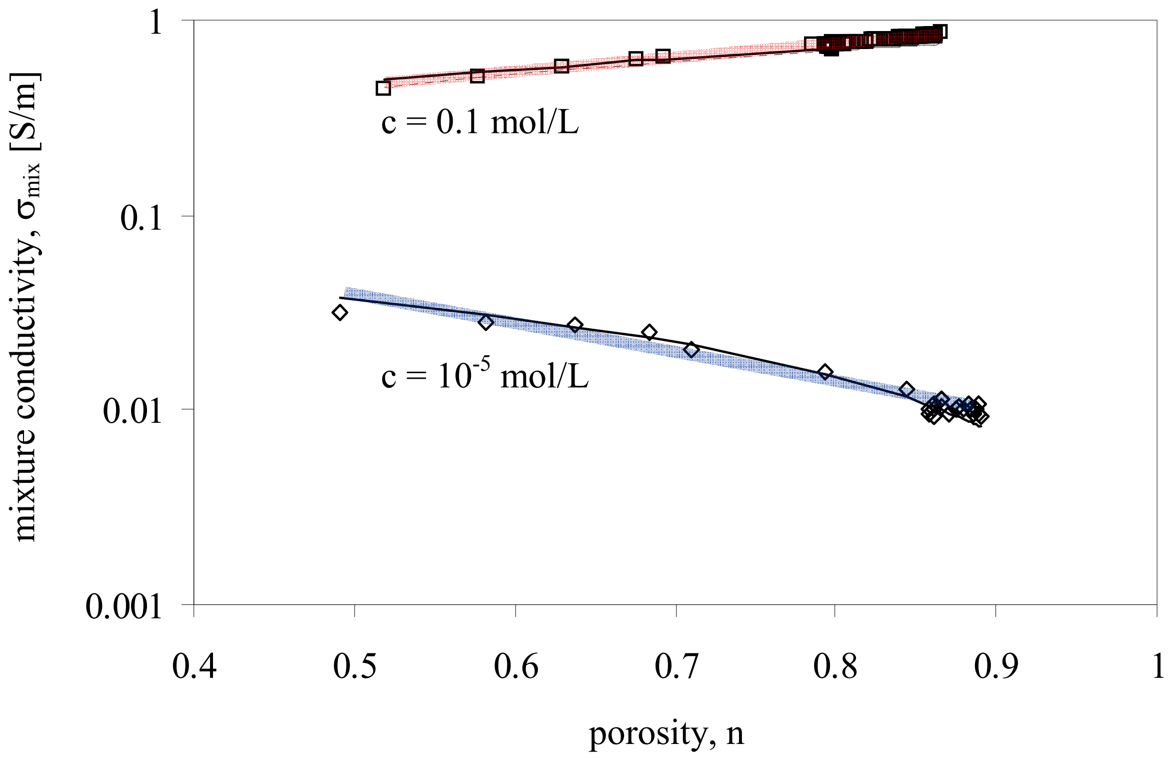
Bulk and Surface Conduction



$$\sigma_{soil} = n\,\sigma_{el} + (1-n)\,2\rho_p\lambda_{ddl}S_a$$

$$\sigma_{soil} = \alpha\ n^{\beta}\,\sigma_{el}$$ (Archie)

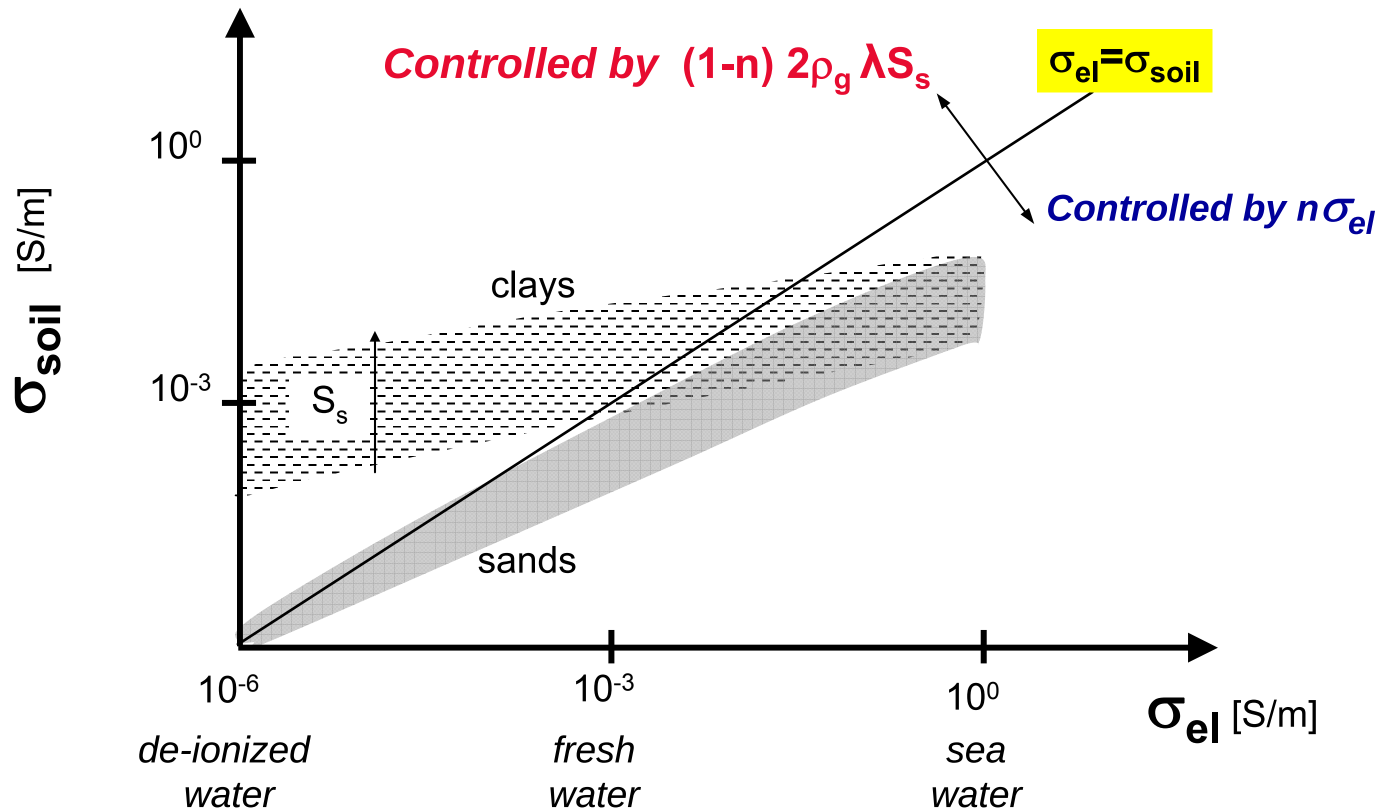
Conductivity: Archie?



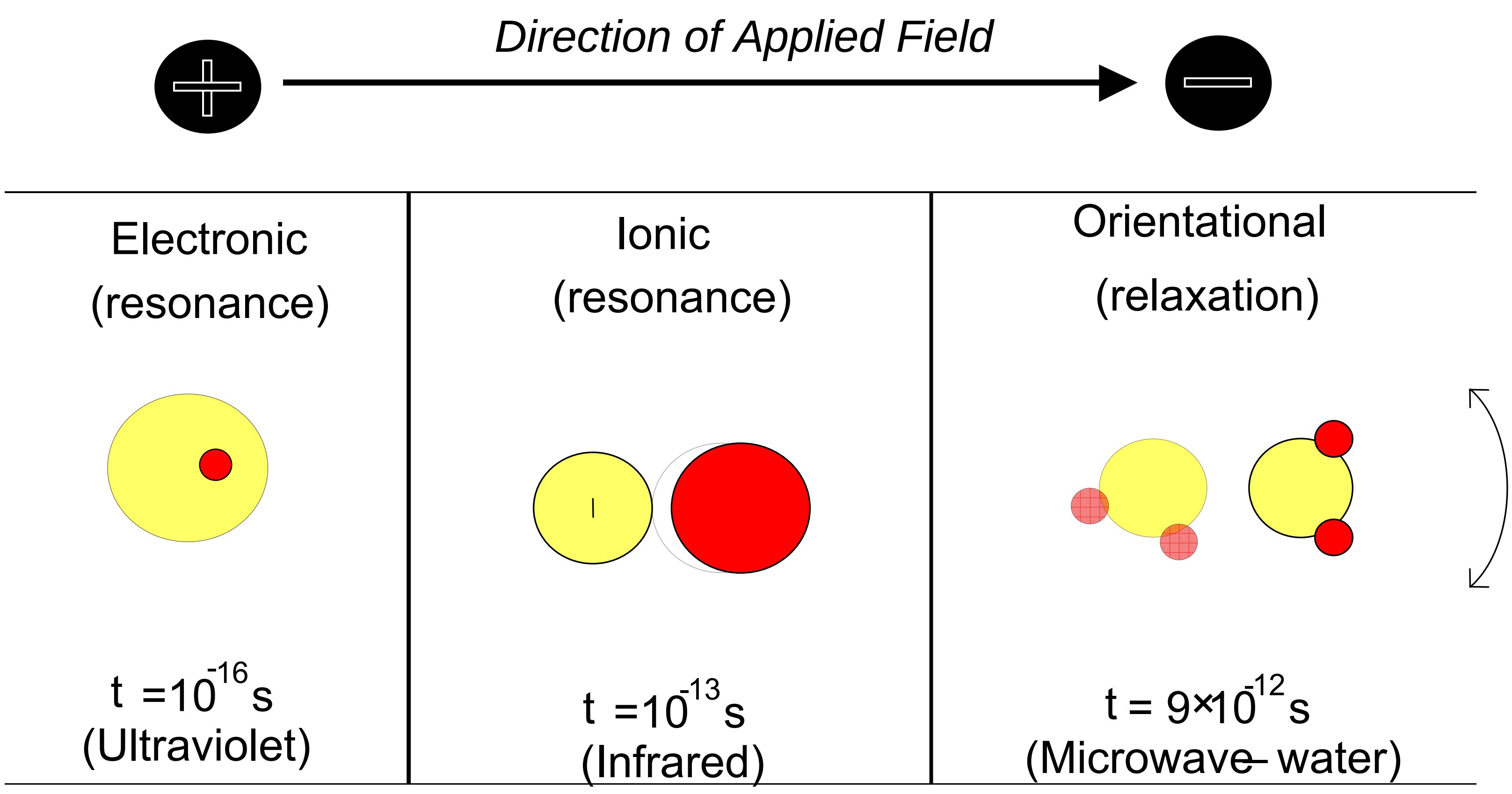
$$\sigma_{soil} = n\,\sigma_{el} + (1-n)\;2\rho_g \lambda S_a$$

K. Klein

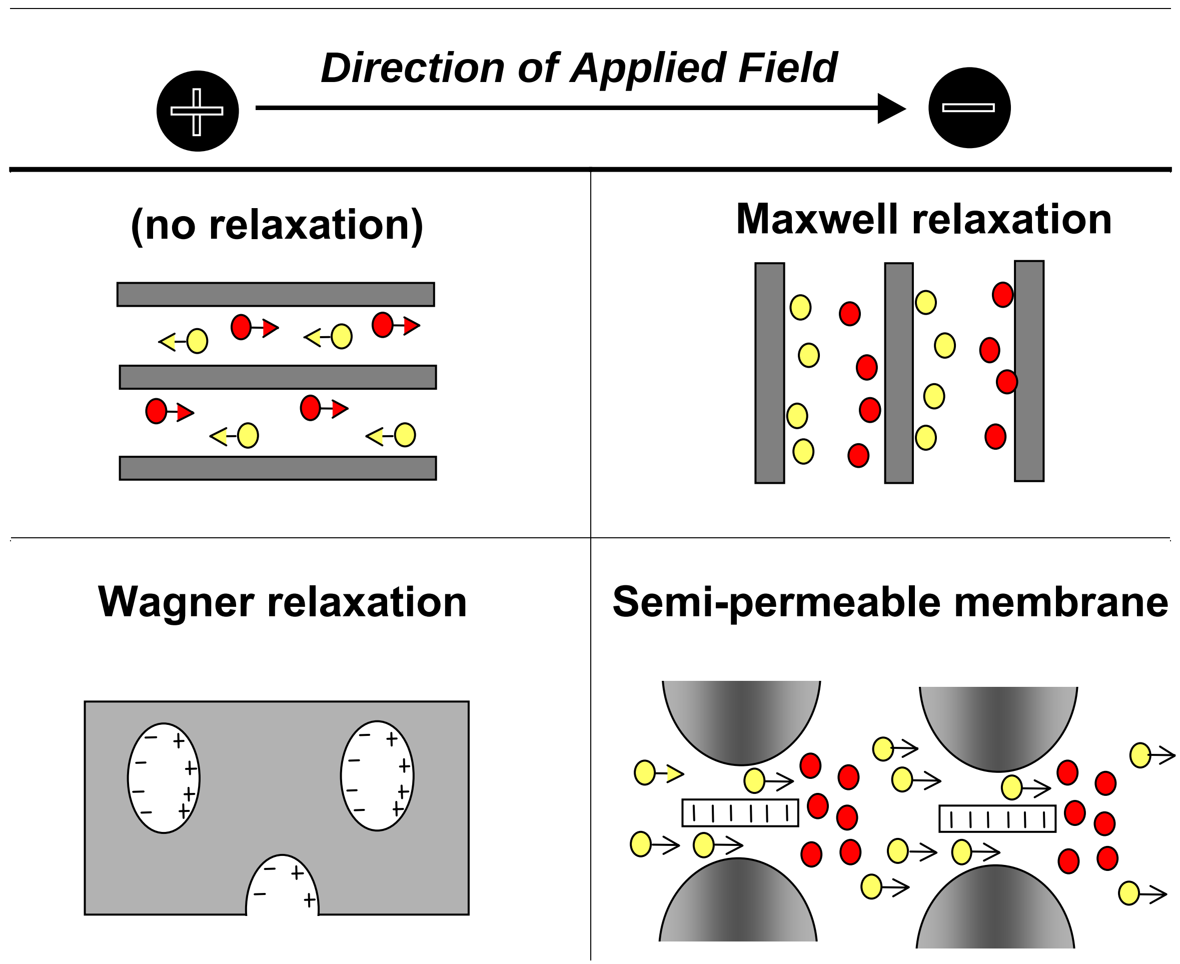
Conductivity - Summary



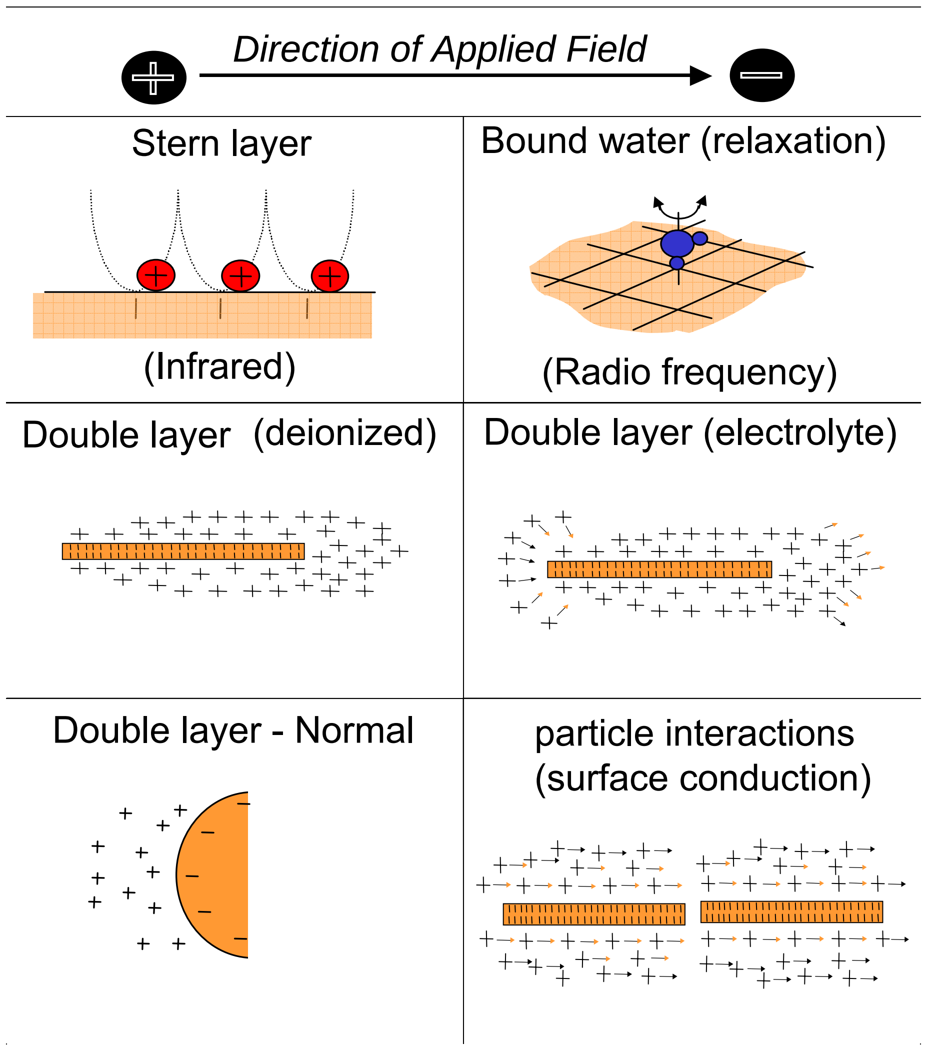
Polarization – Single phase



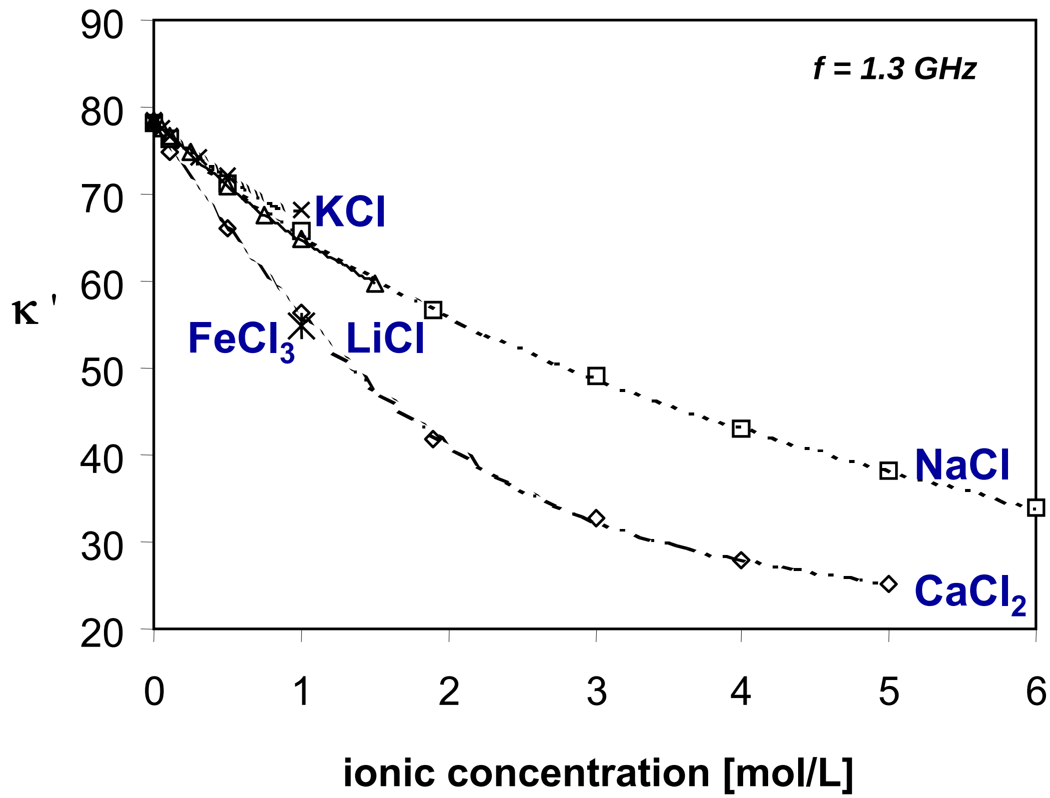
Two-phase media - Spatial polarization



Double layer effects

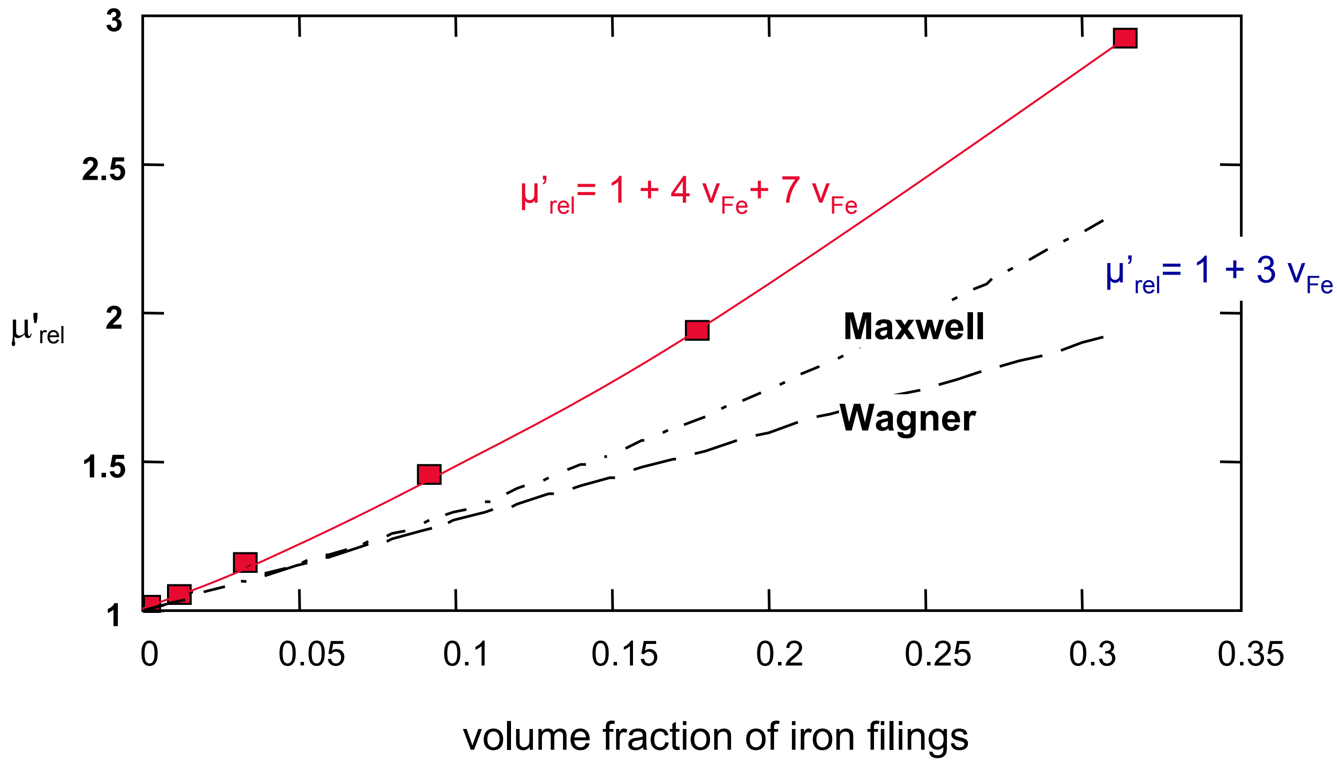


Water-Ion Interaction



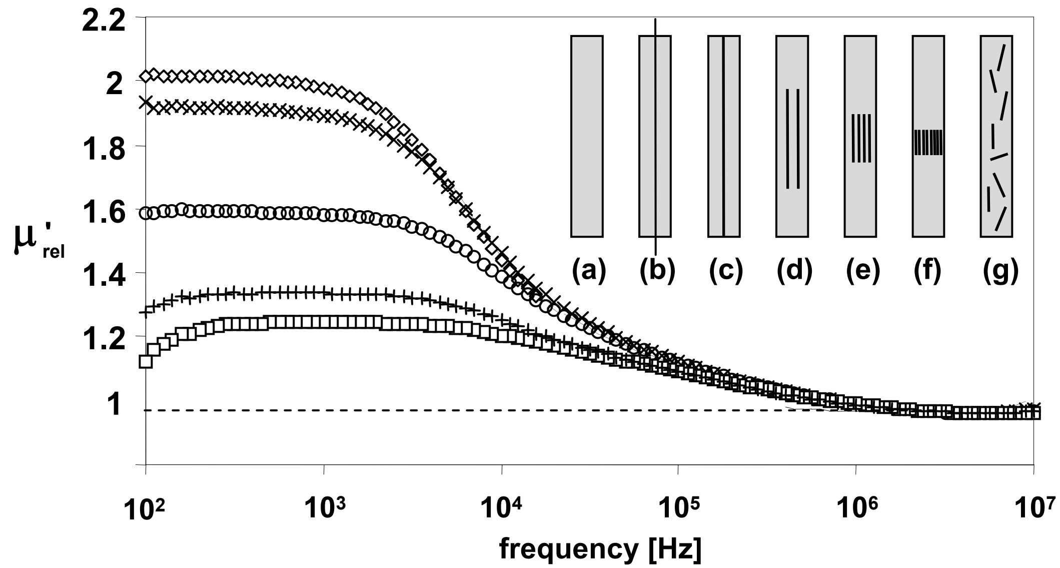
Permeability

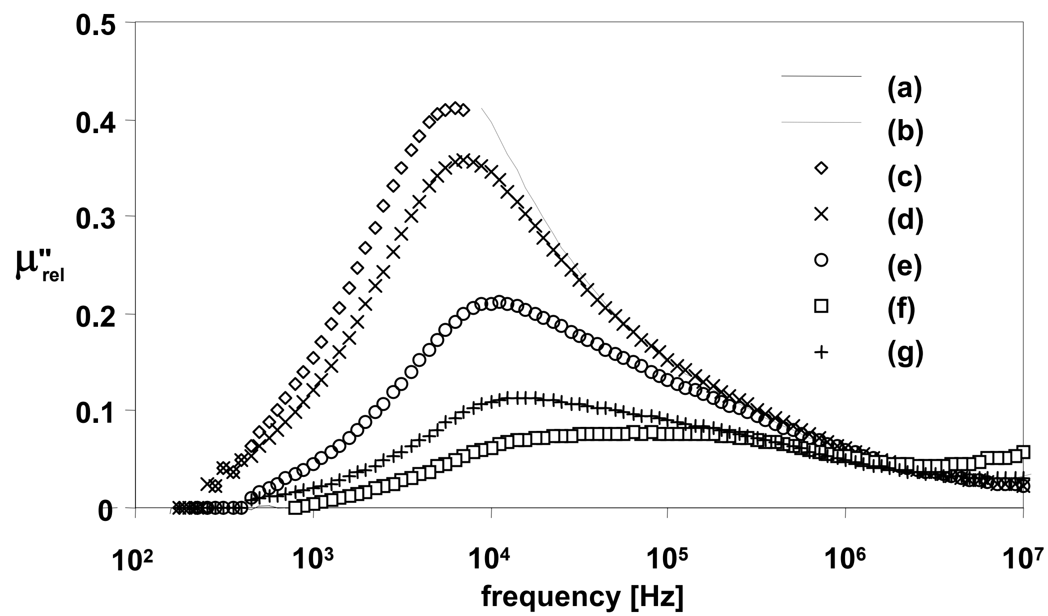
iron fillings in kaolinite – f = 10 kHz



Permeability

iron in kaolinite

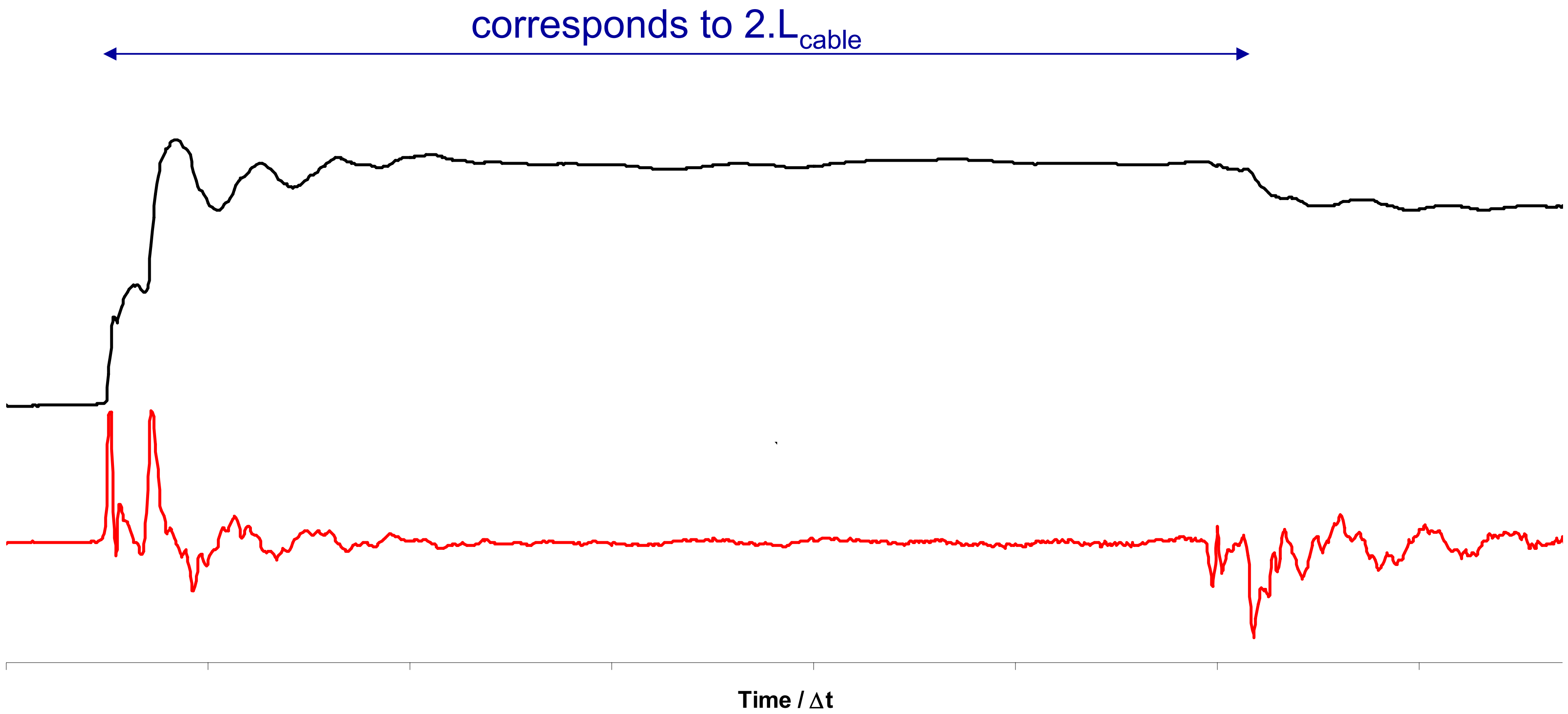




All data by Dante Fratta (U. Wisconsin)

TDR measurements

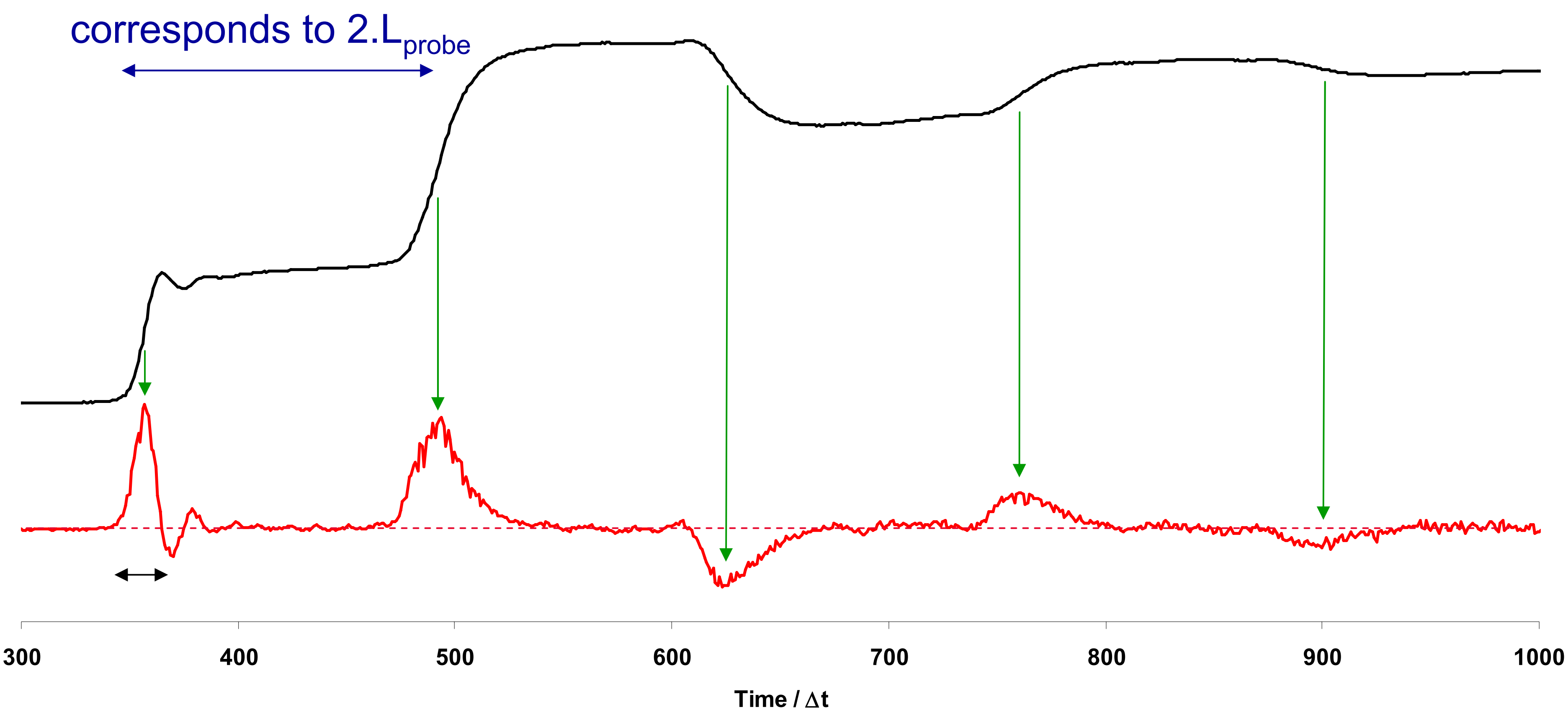
The Cable



the probe = complex end-reflector

signal changed sign at equipment

The Probe

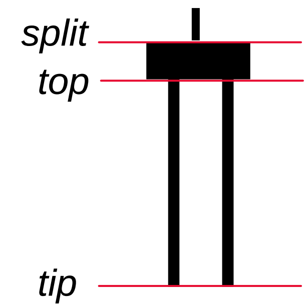


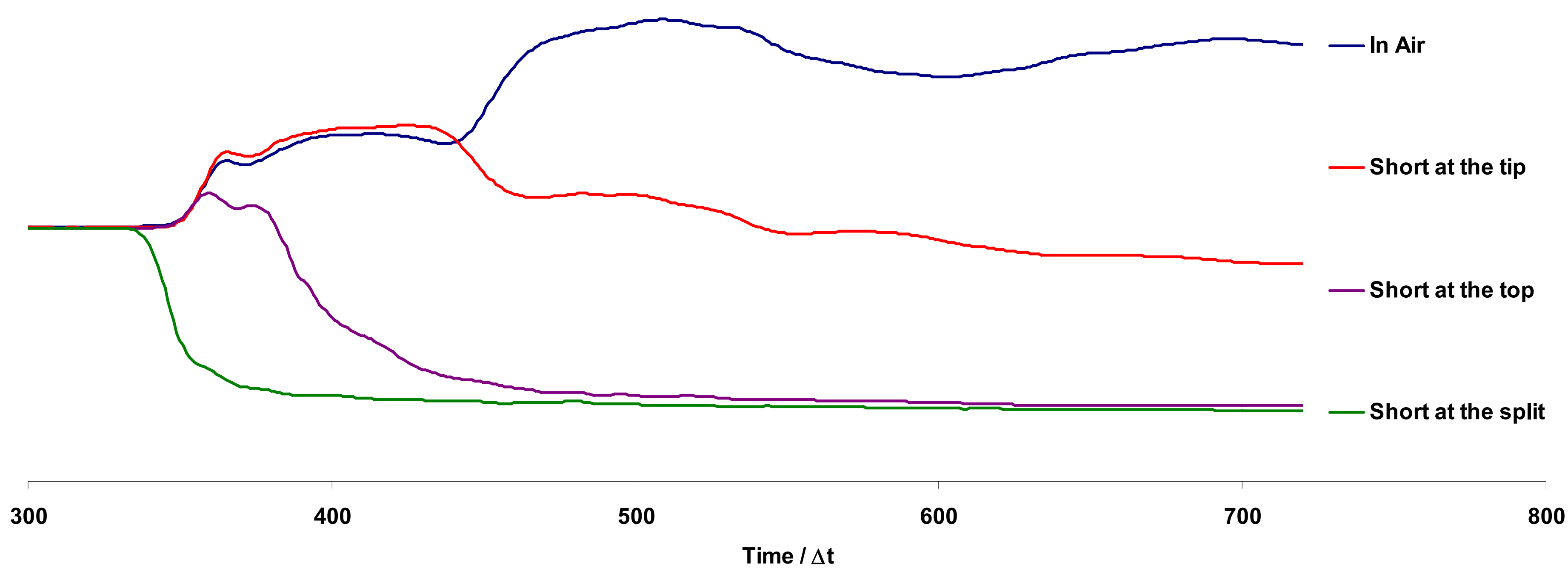
f~ 1 to 3 GHz

dispersion

multiples

Short



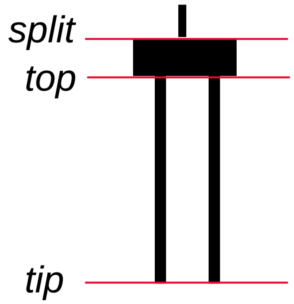


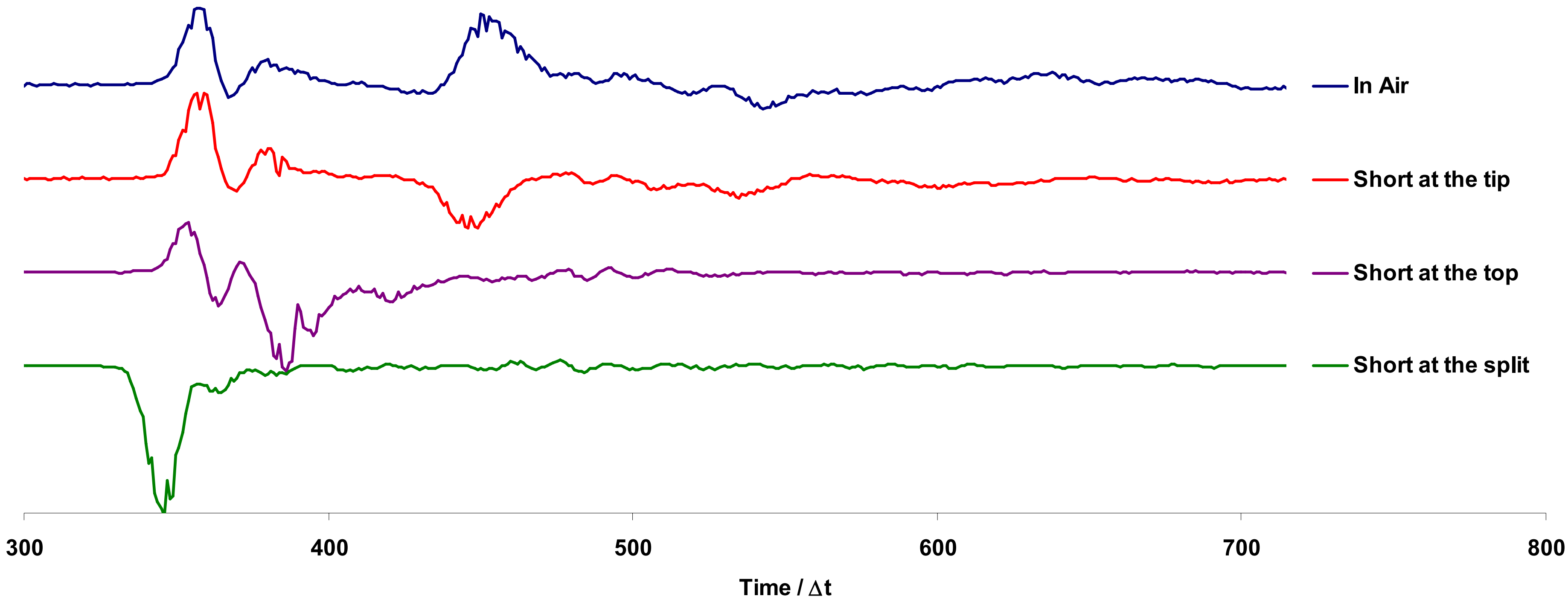
where is zero-time?

composite reflection at top

open and short tip impedance

Short



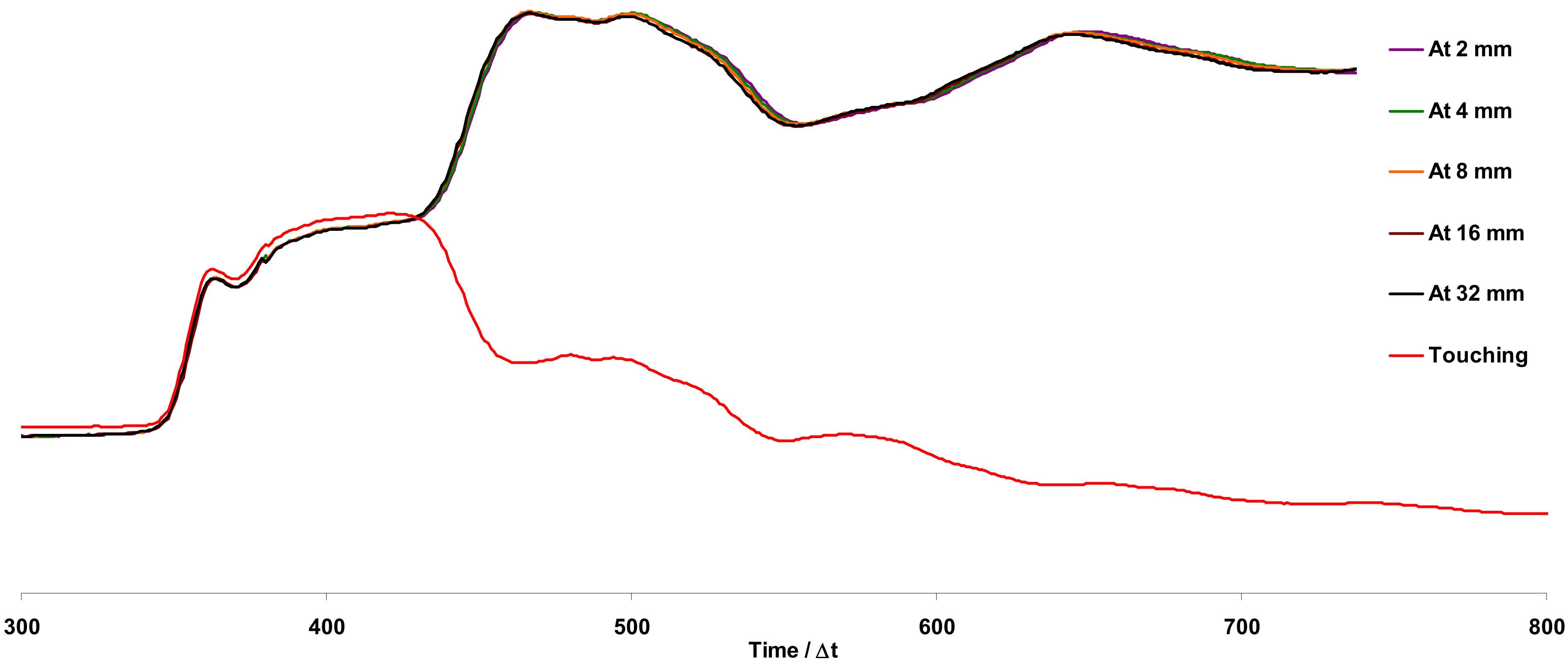


where is zero-time?

composite reflection at top

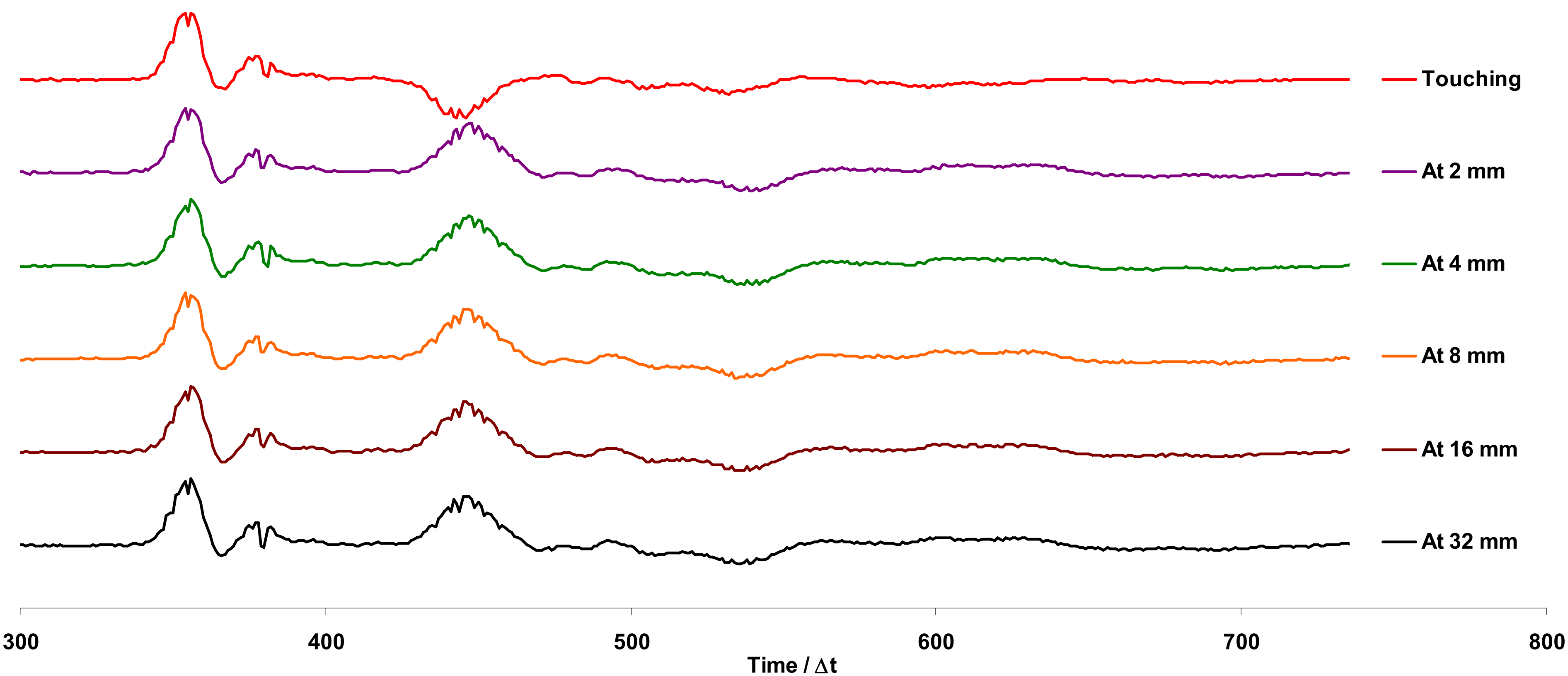
open and short tip impedance

Boundaries: Normal Plate



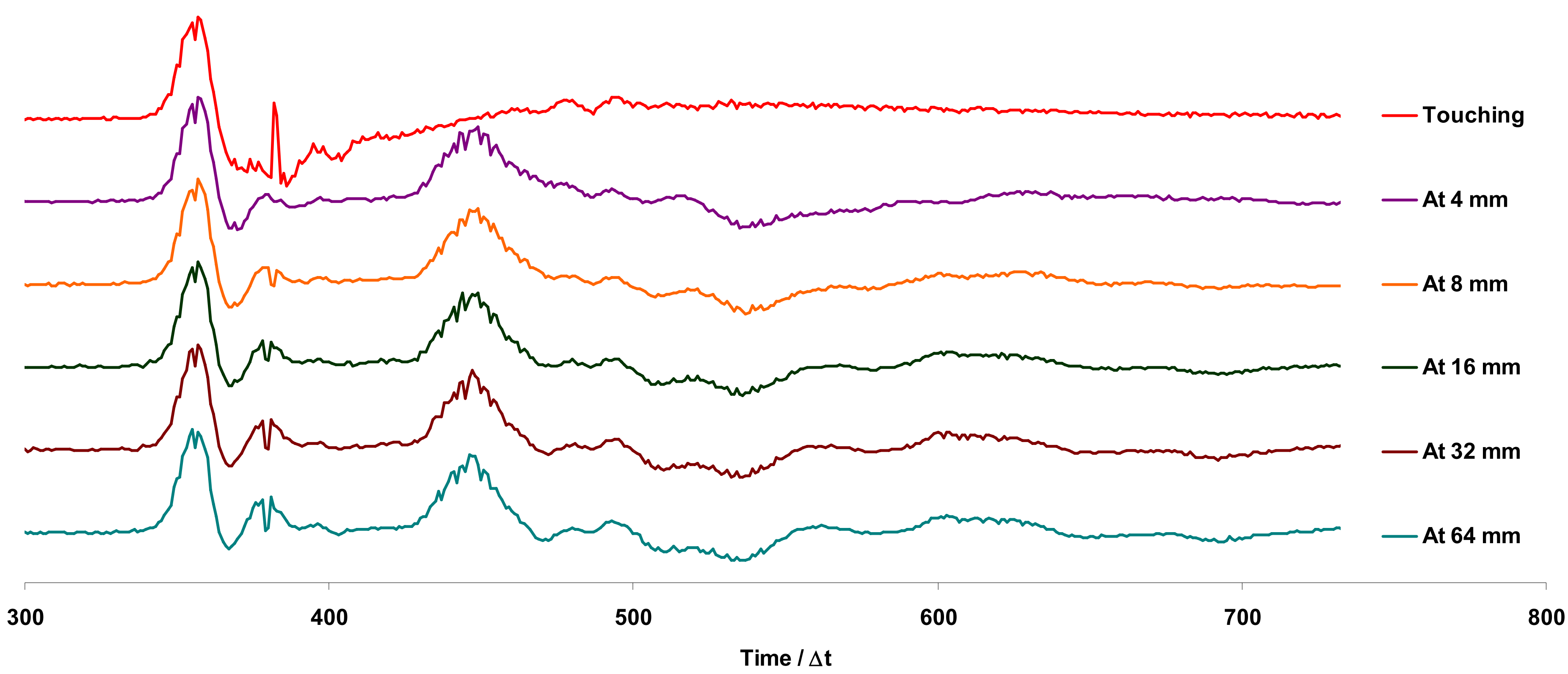
does not see ahead of tip

Boundaries: Normal Plate



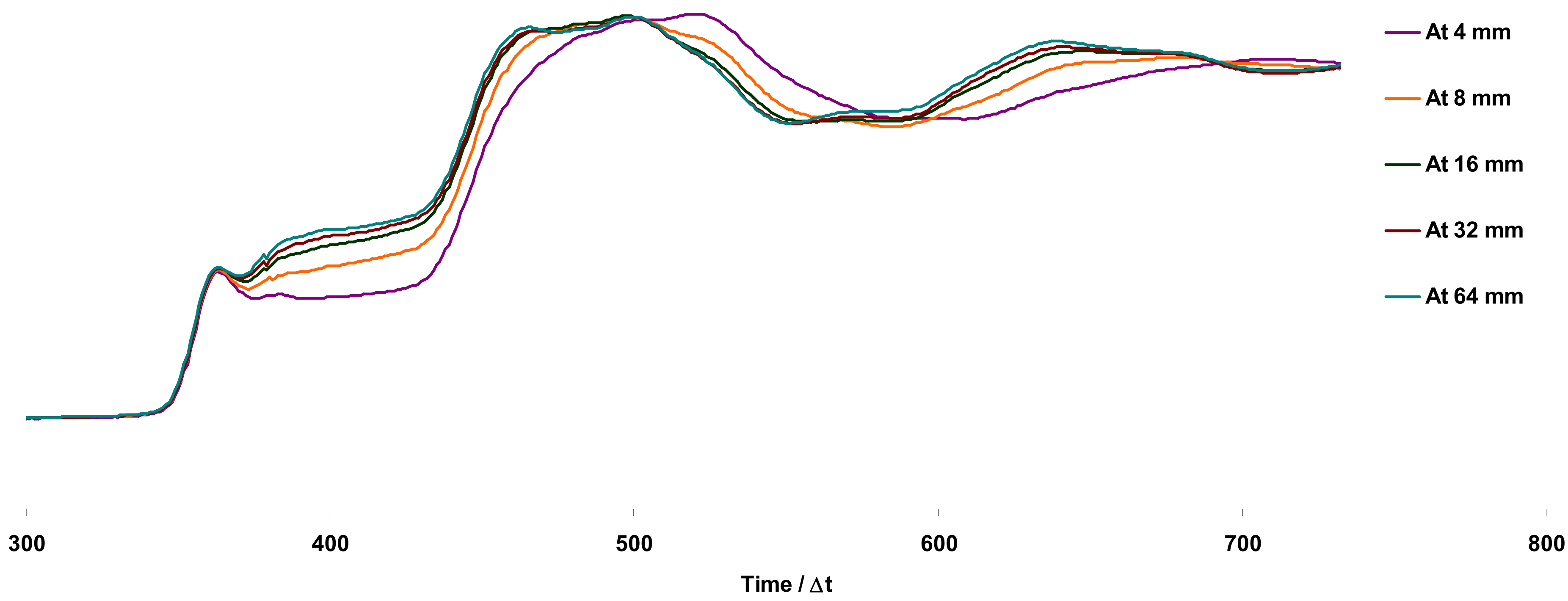
does not see ahead of tip

Boundaries: Parallel Plate



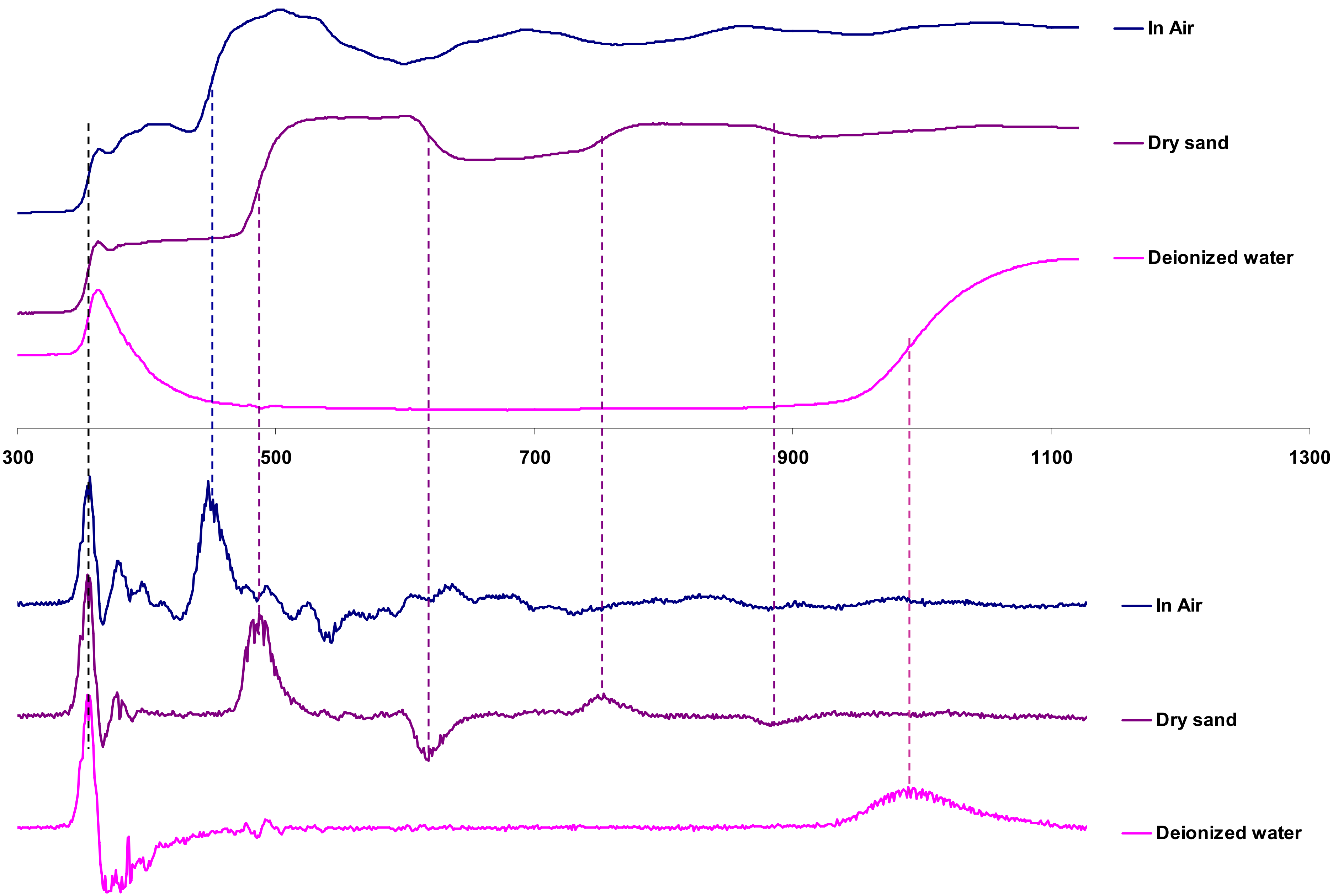
does not feel outside inter-rod ?

Boundaries: Parallel Plate



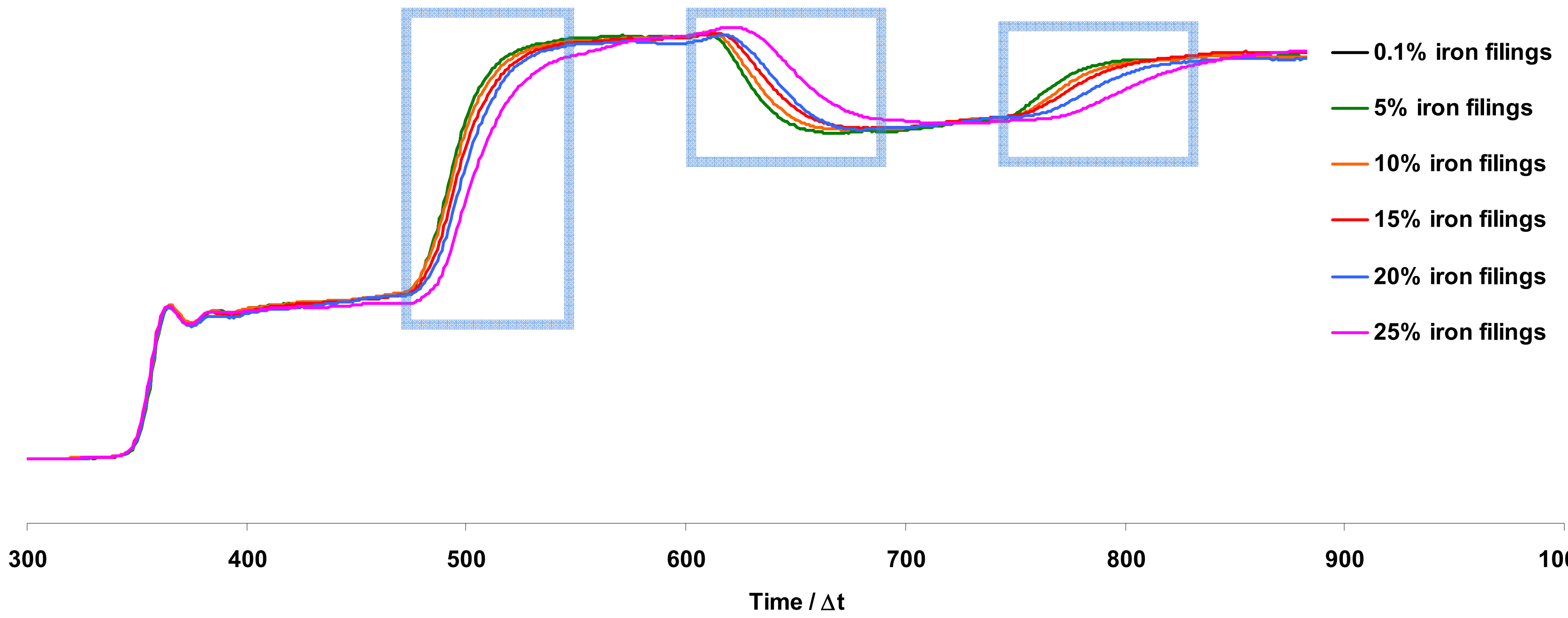
H-field effect!

Permittivity



Permeability

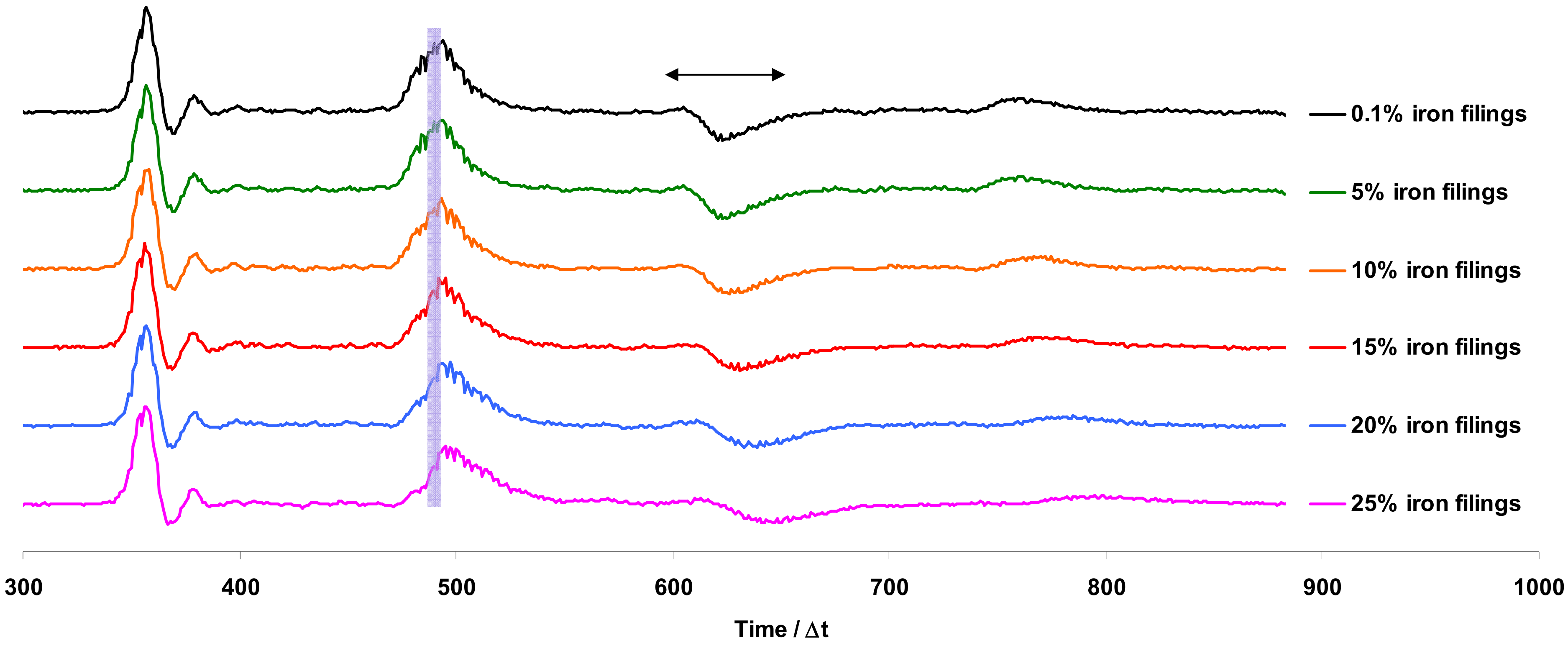
Sand +



expect minor effect

Permeability

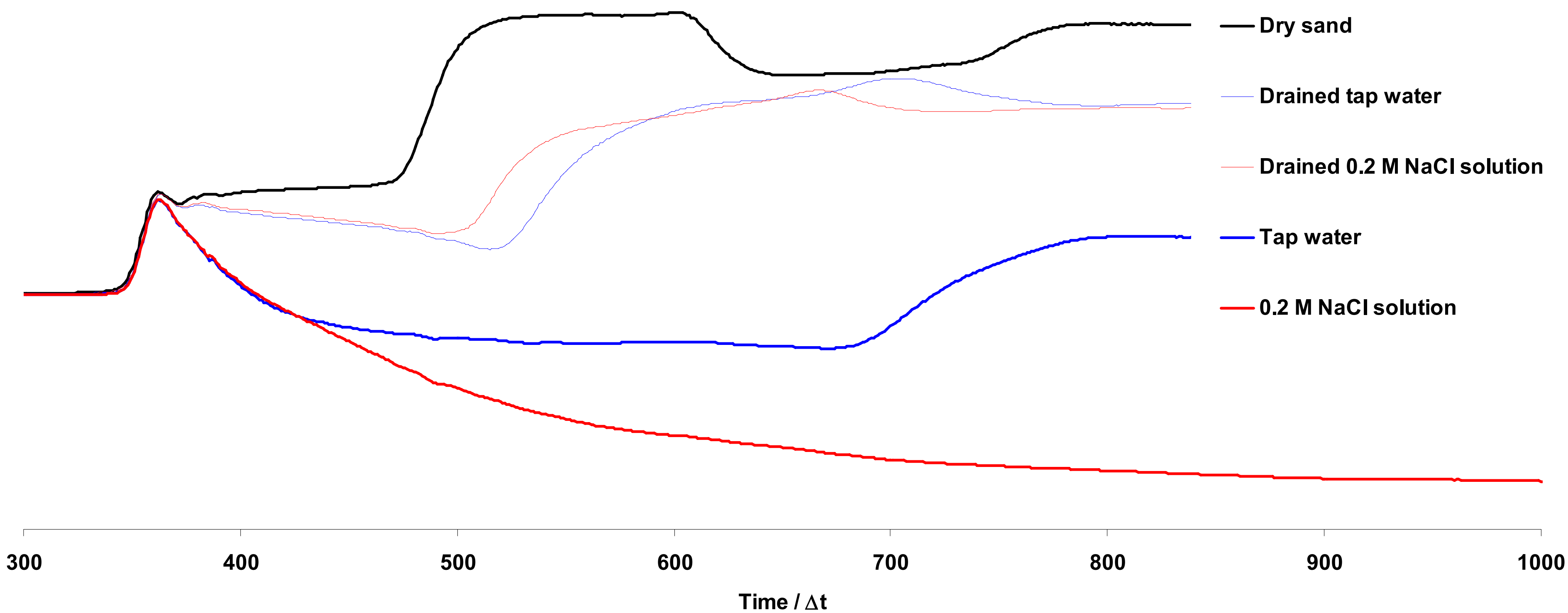
Sand +



expect minor effect

Conductivity

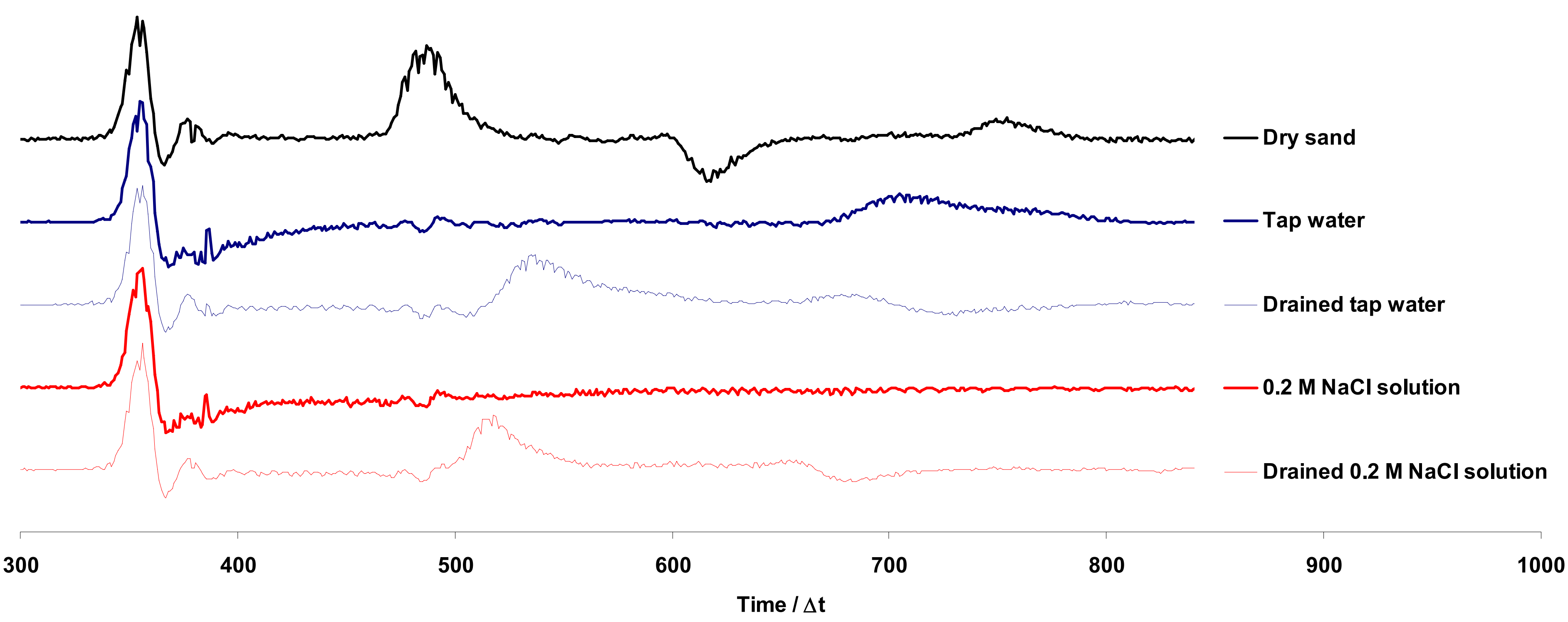
Sand



good assessment of conductivity

Conductivity

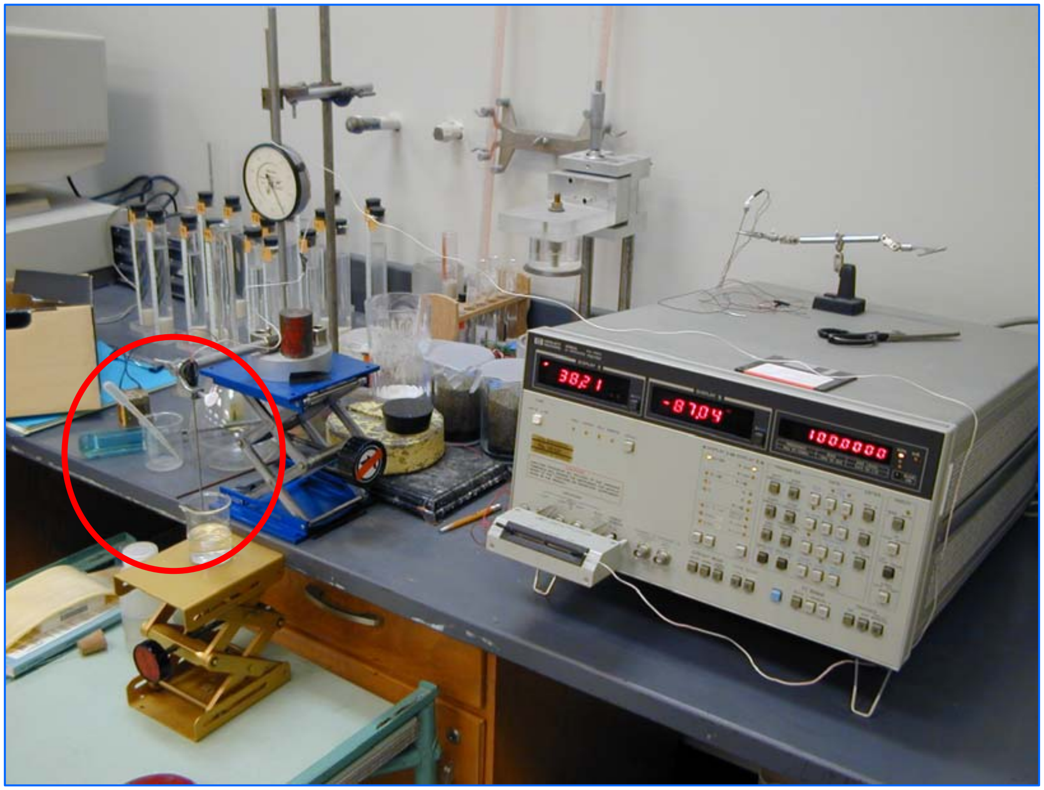
Sand

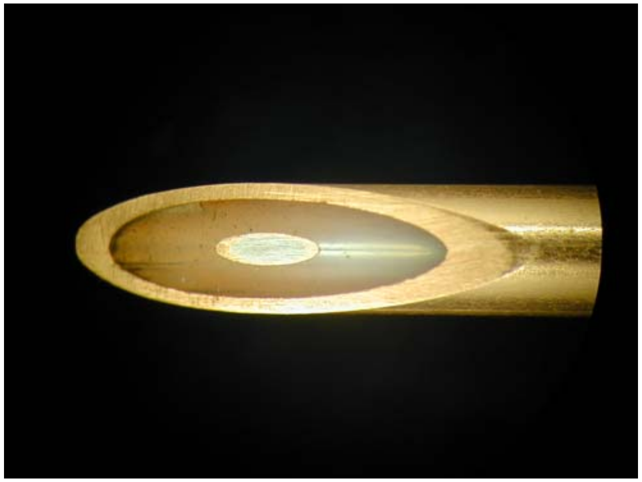


recall skin depth

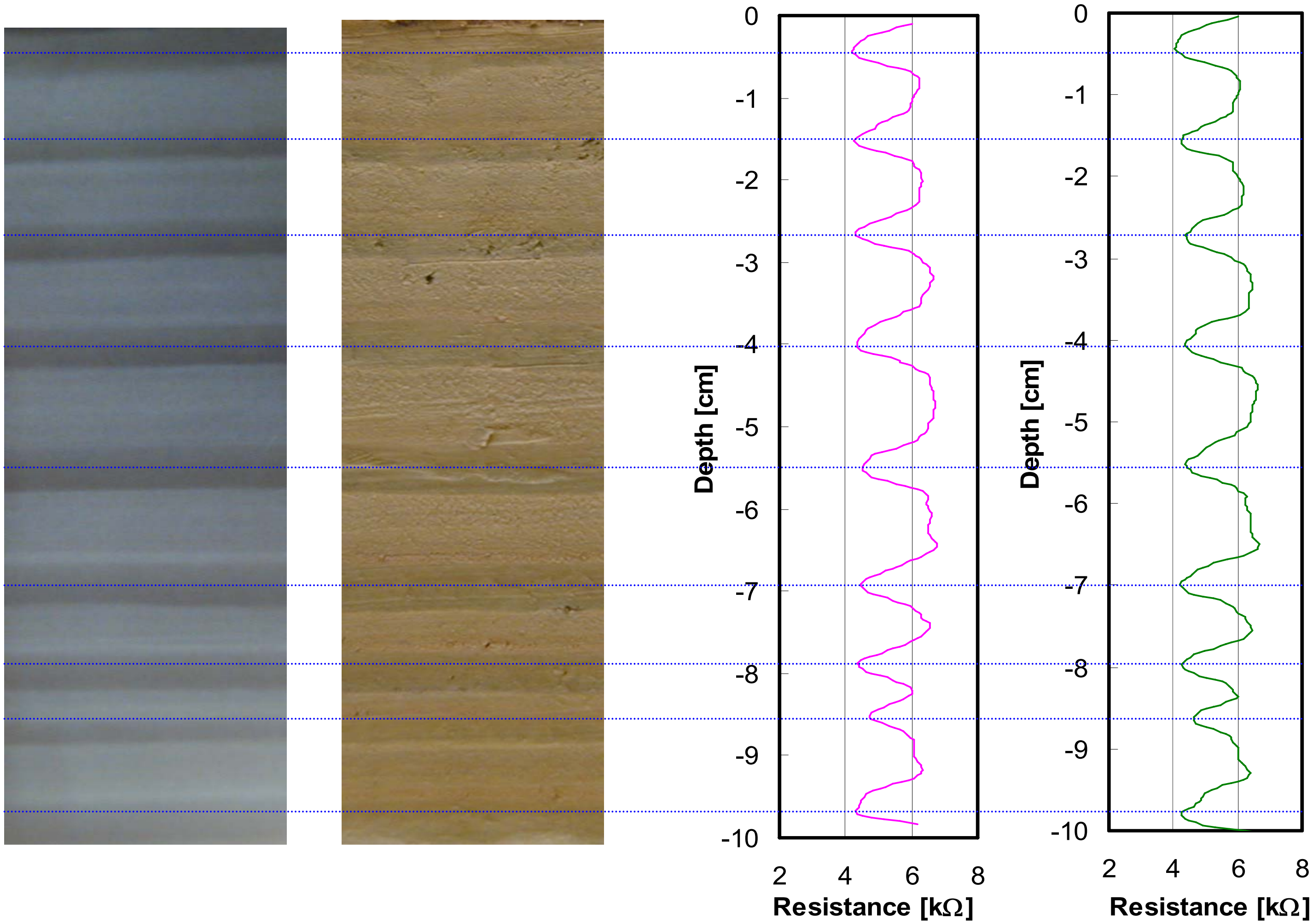
may not see tip reflection

Heterogeneity – Layering





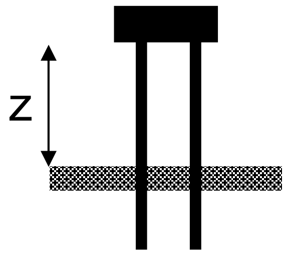
Varved Clay

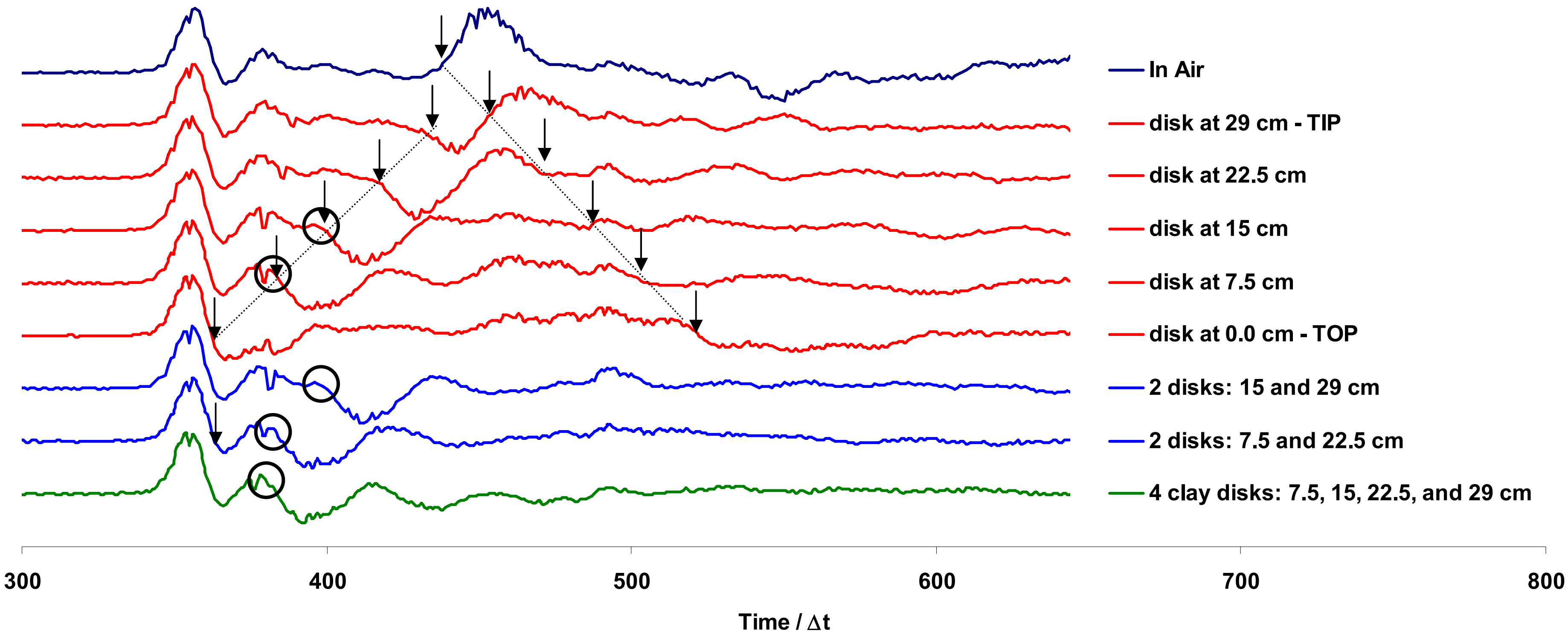


X-Ray **Photograph** **Needle probe measurements**

Cho, Lee

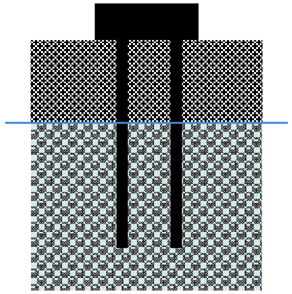
Heterogeneity - Layering

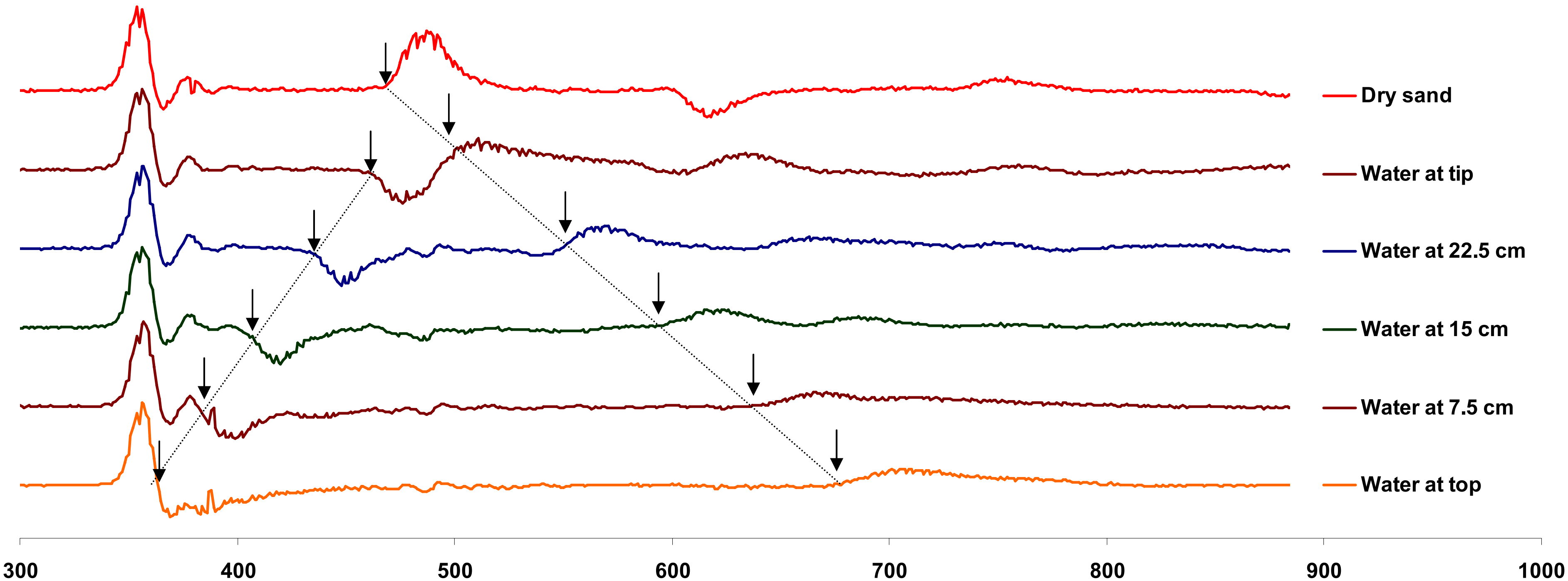




a clay seam may hide the rest
(very high mismatch in this case)

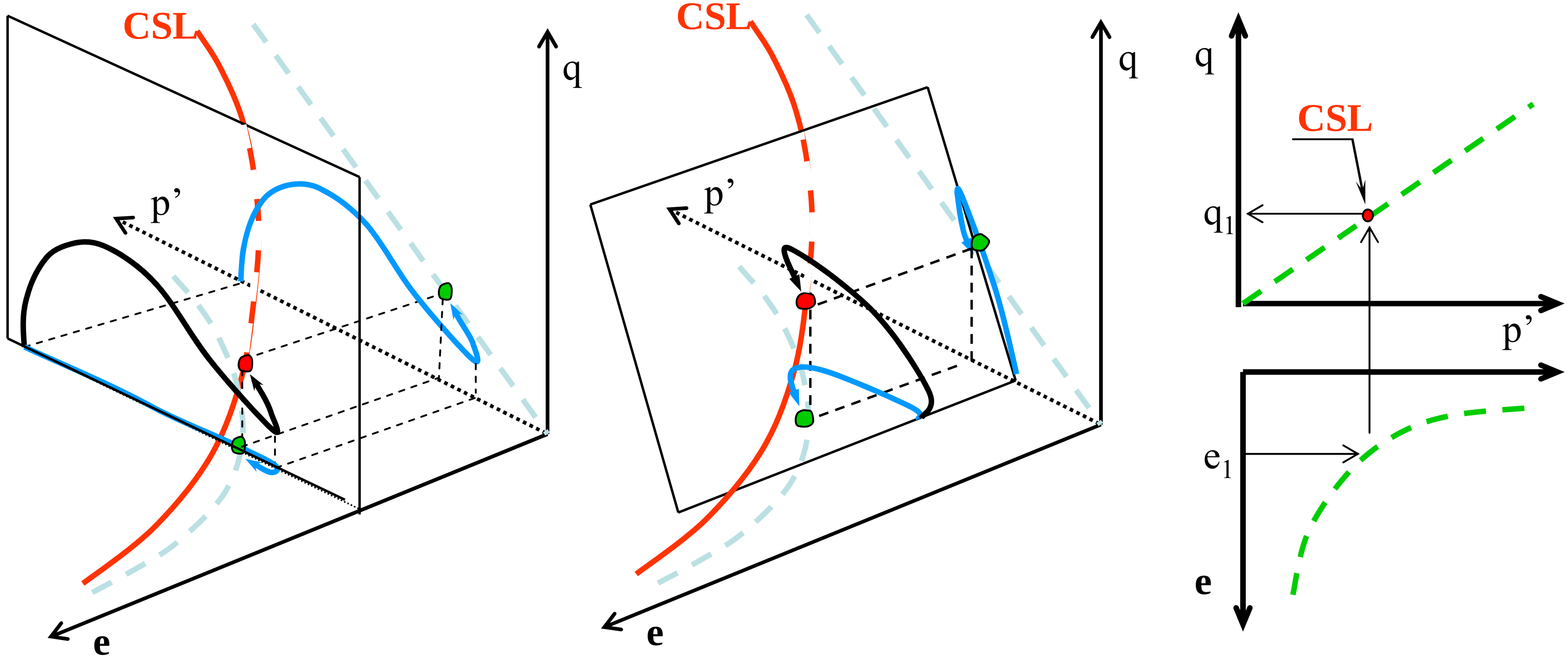
Heterogeneity in Water Content





more than one primary reflections

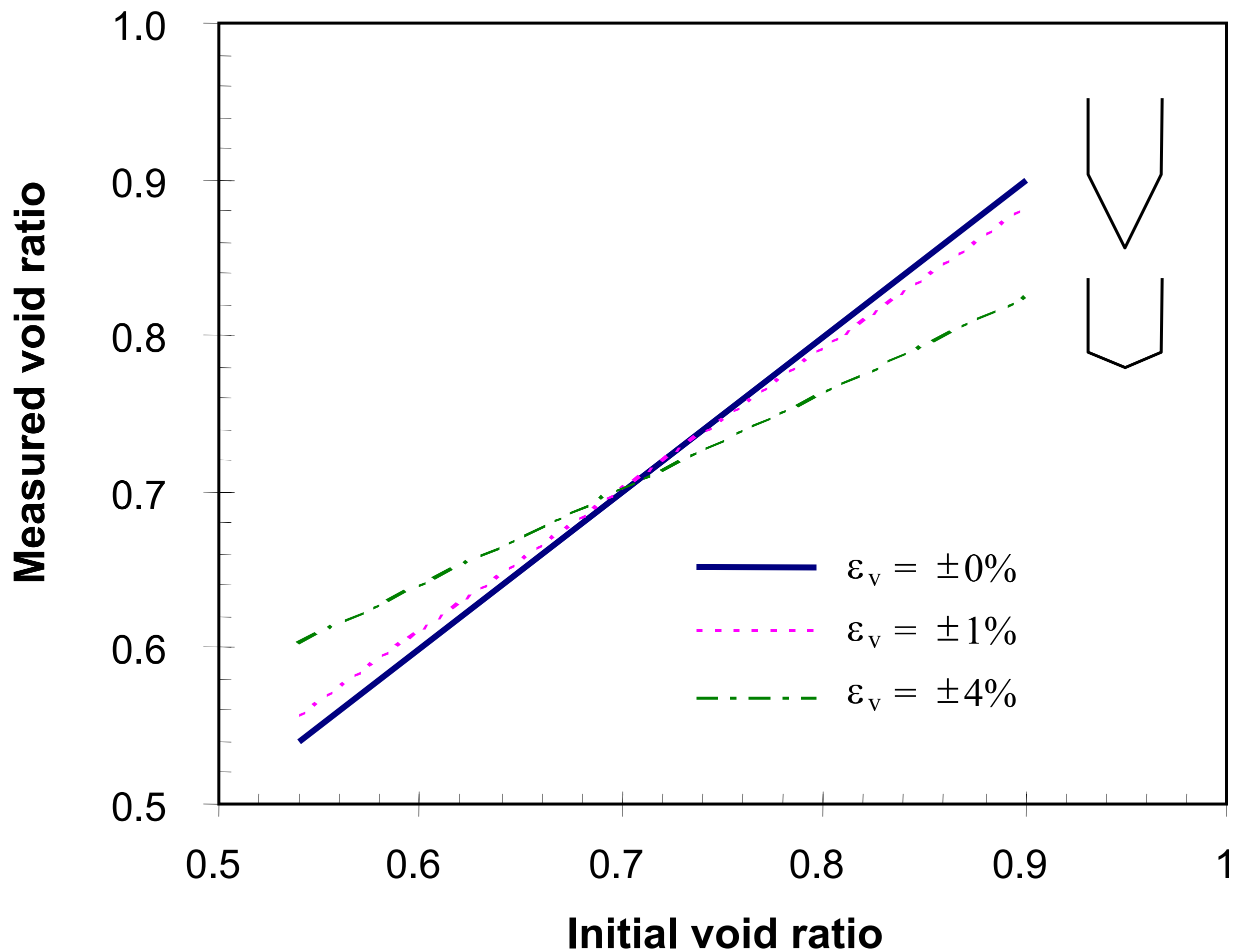
Insertion Effects



Undrained

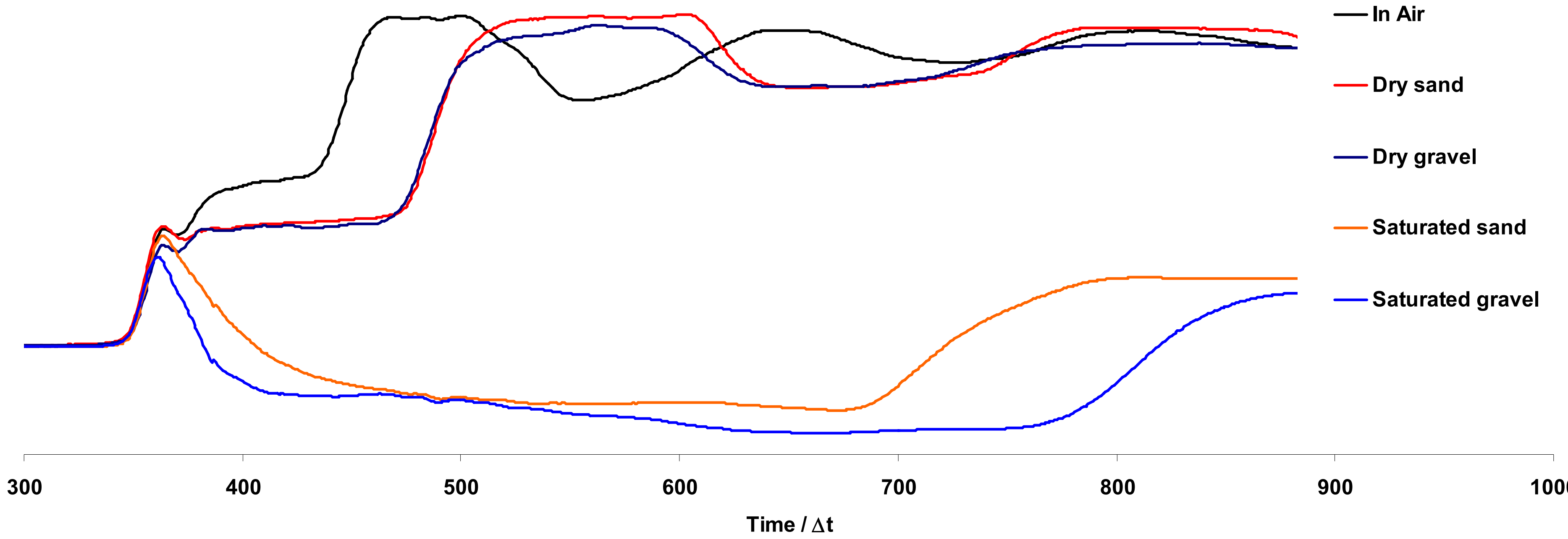
Drained

Insertion: Volumetric Strain = f(void ratio)



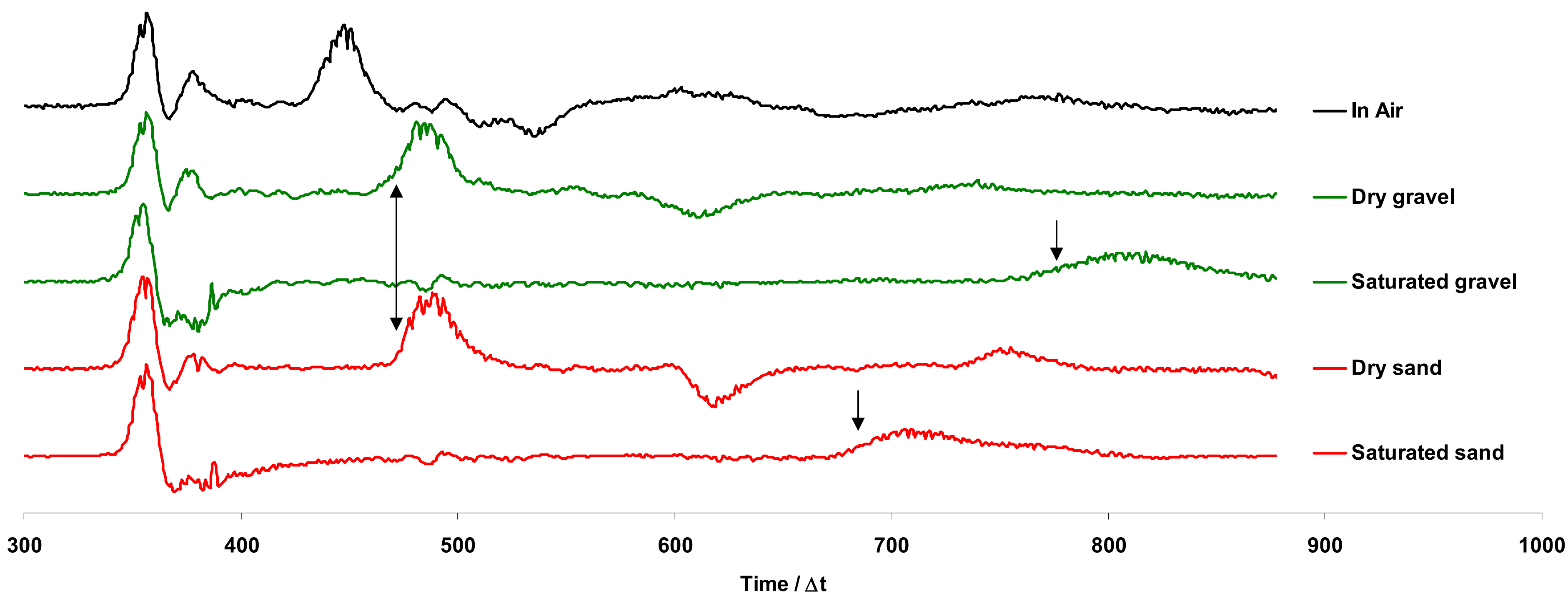
Large vs. Small Particles

Gravel – d_{50}= 20 mm



Large vs. Small Particles

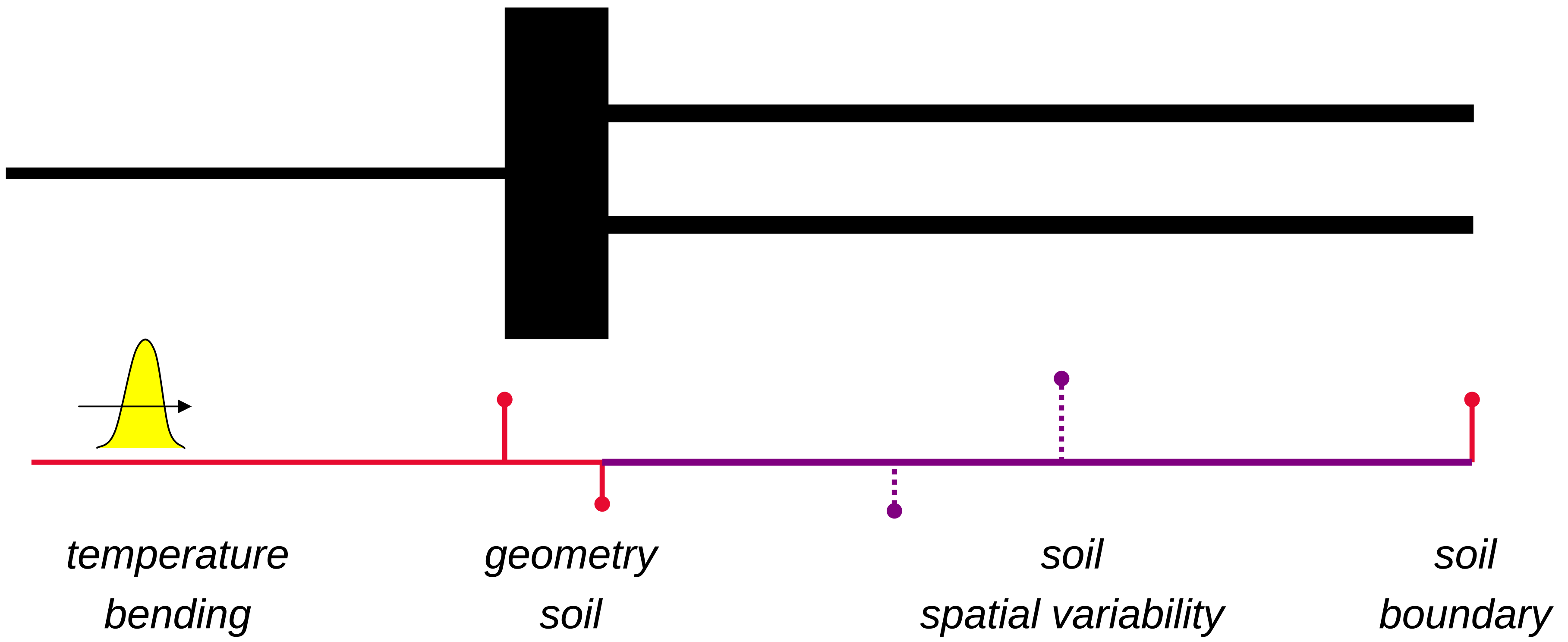
Gravel – d_{50}= 20 mm



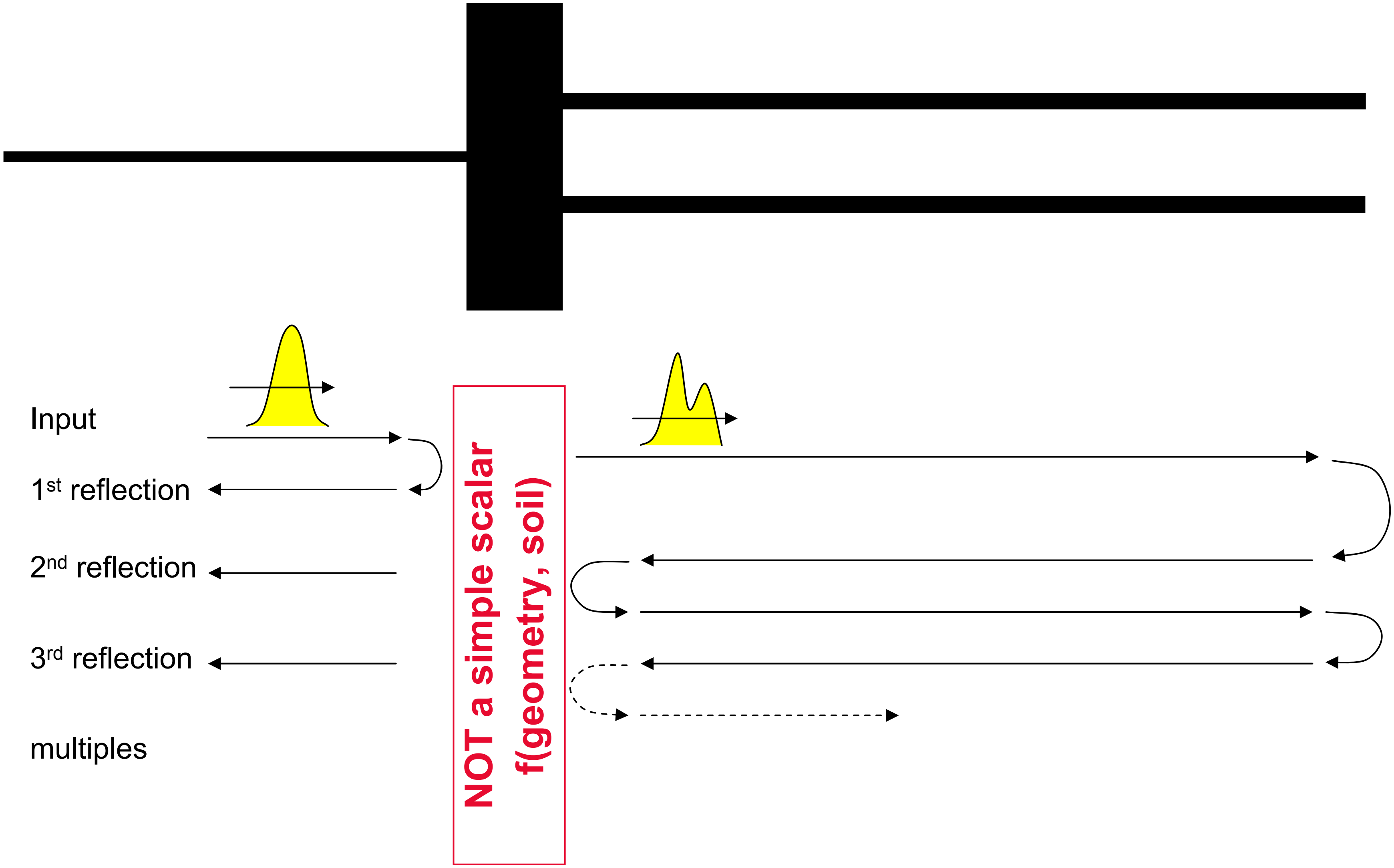
higher local porosity in gravel

Brillouin LP filter?

Summary


temperature
bending
geometry
soil
soil
spatial variability
soil
boundary

Summary



Input
1st reflection
2nd reflection
3rd reflection
multiples
NOT a simple scalar
f(geometry, soil)

Summary

The connection to probe:

sequence of electrical and geometrical changes

response is a function of the soil itself

when is time zero? what signal gets to the soil?

Compare the 2nd and 3rd reflections (if 3rd is not lost in noise)

Geometric dispersion + attenuation: signal widens

Ferromagnetism: expect small effect

Insertion effects and preferential packing (aggravated in coarse soils)

Complex signal: consider spatial variability

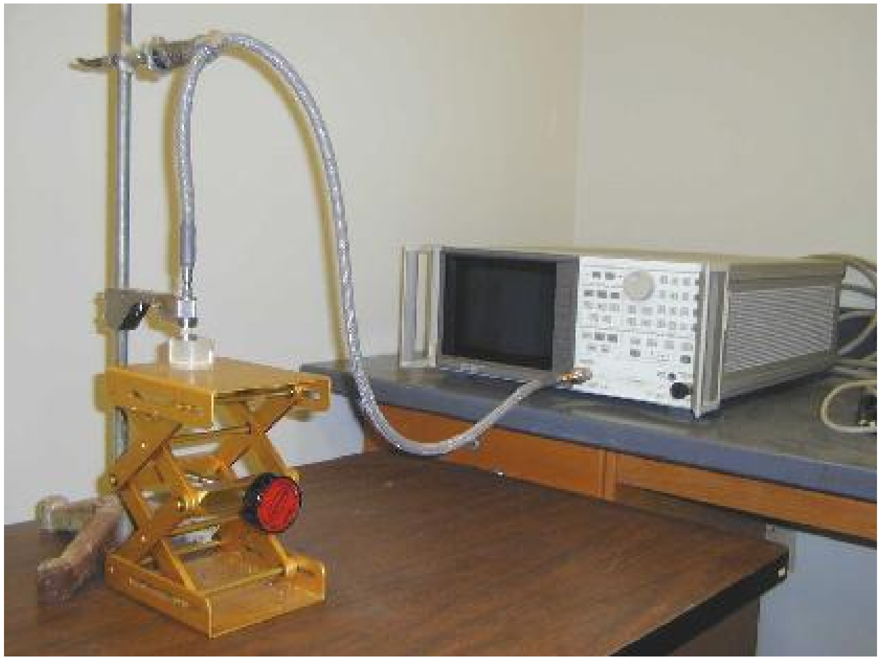
multiple interpretations of multiples

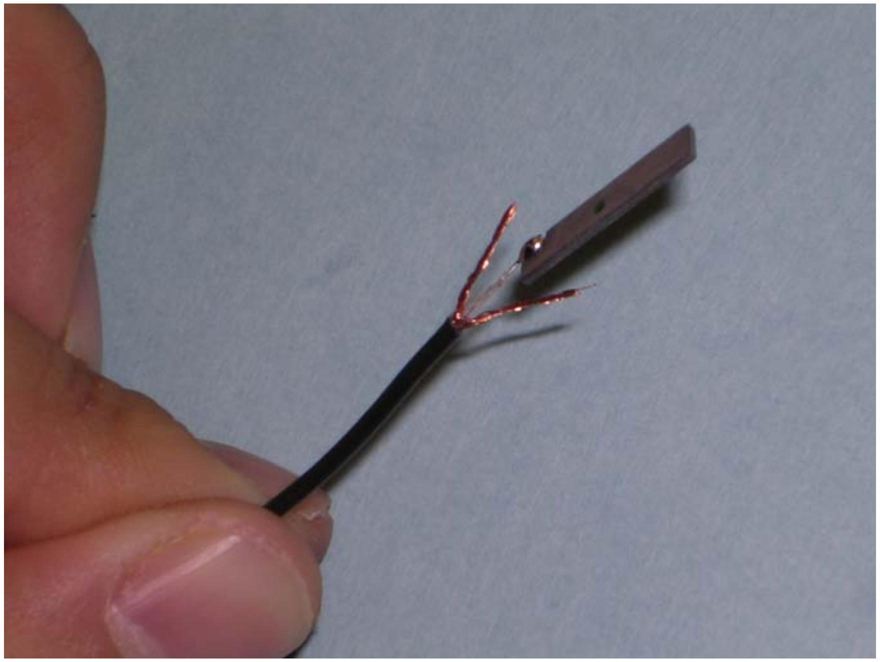
many unknowns → inversion may be ill defined

Information conservation → simple models (Ockham's criterion)

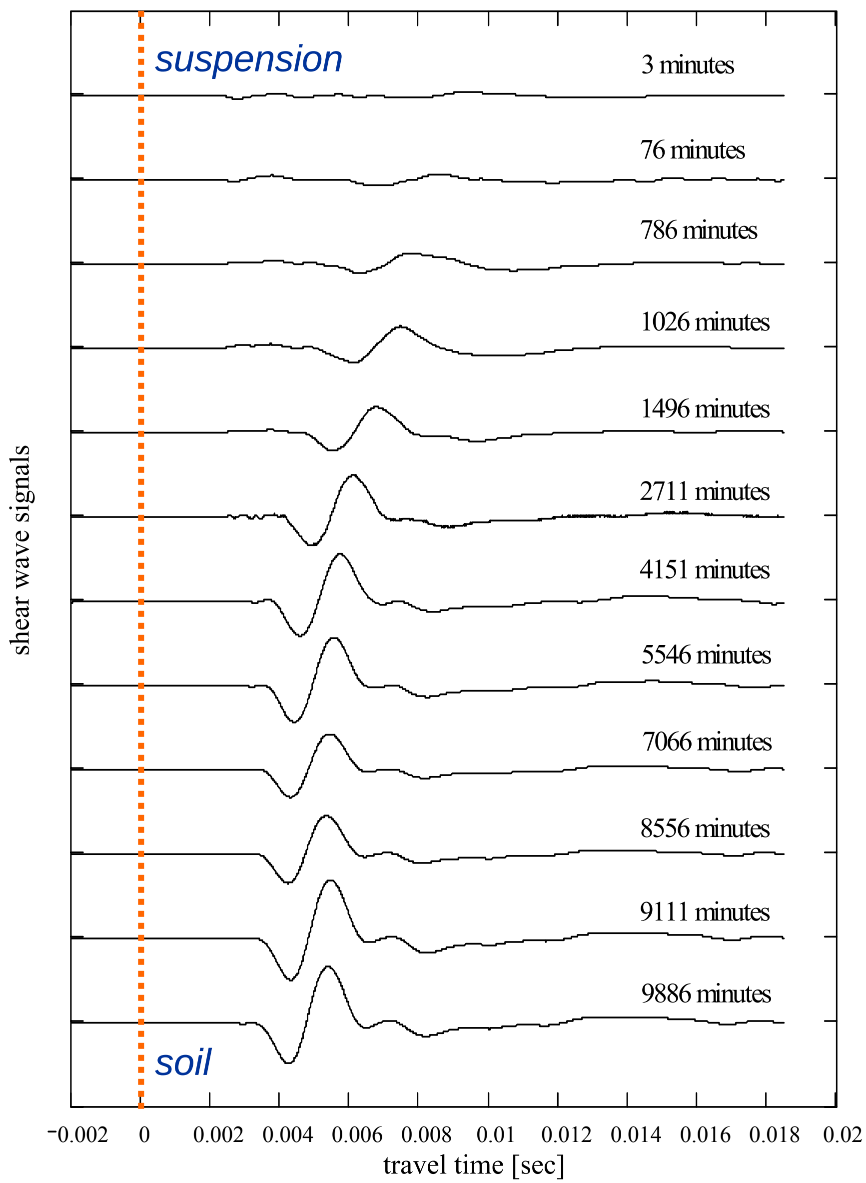
process monitoring

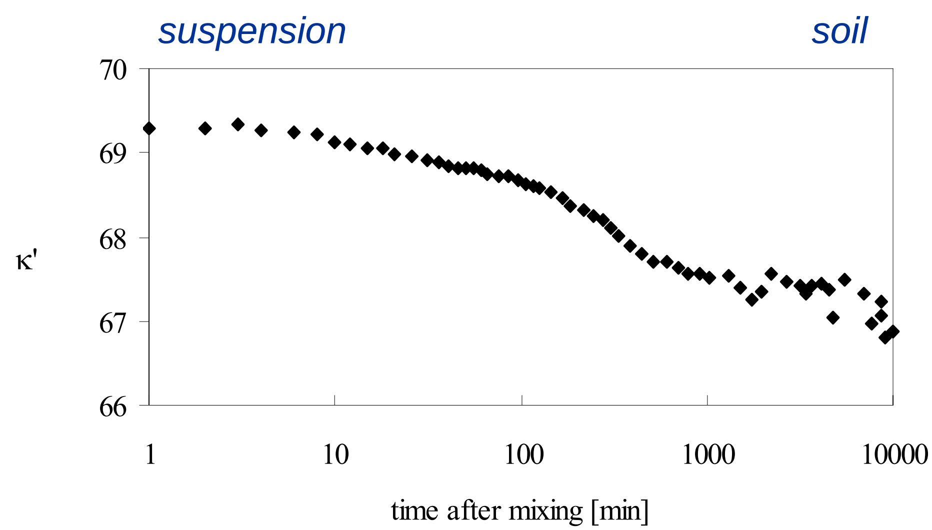
Measurements





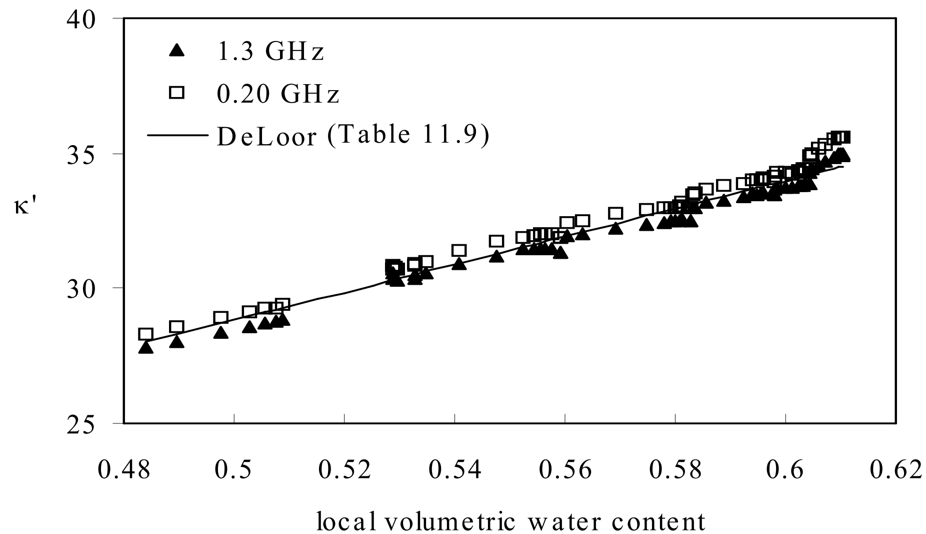
Sedimentation



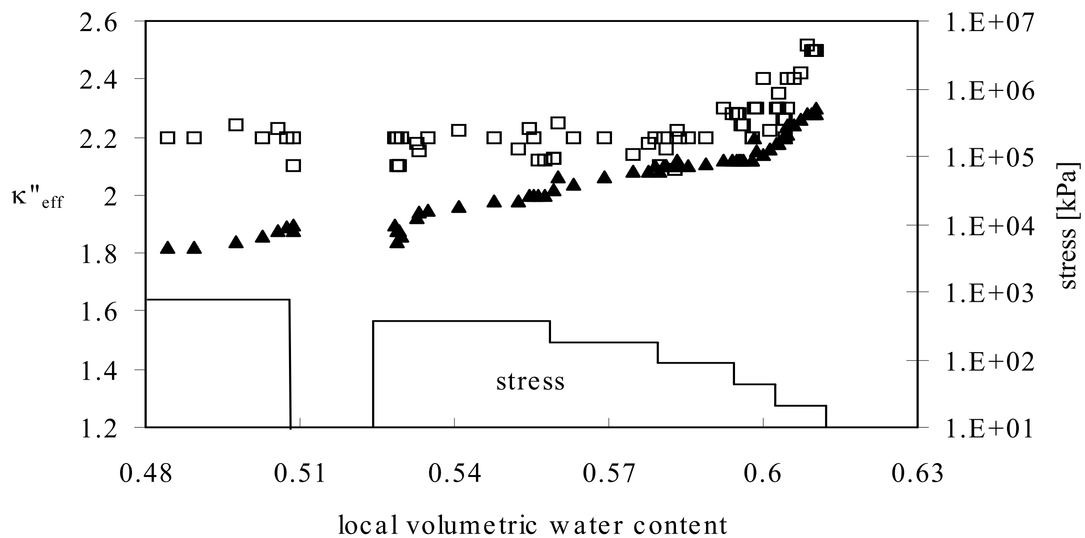


K. Klein

Pressure diffusion

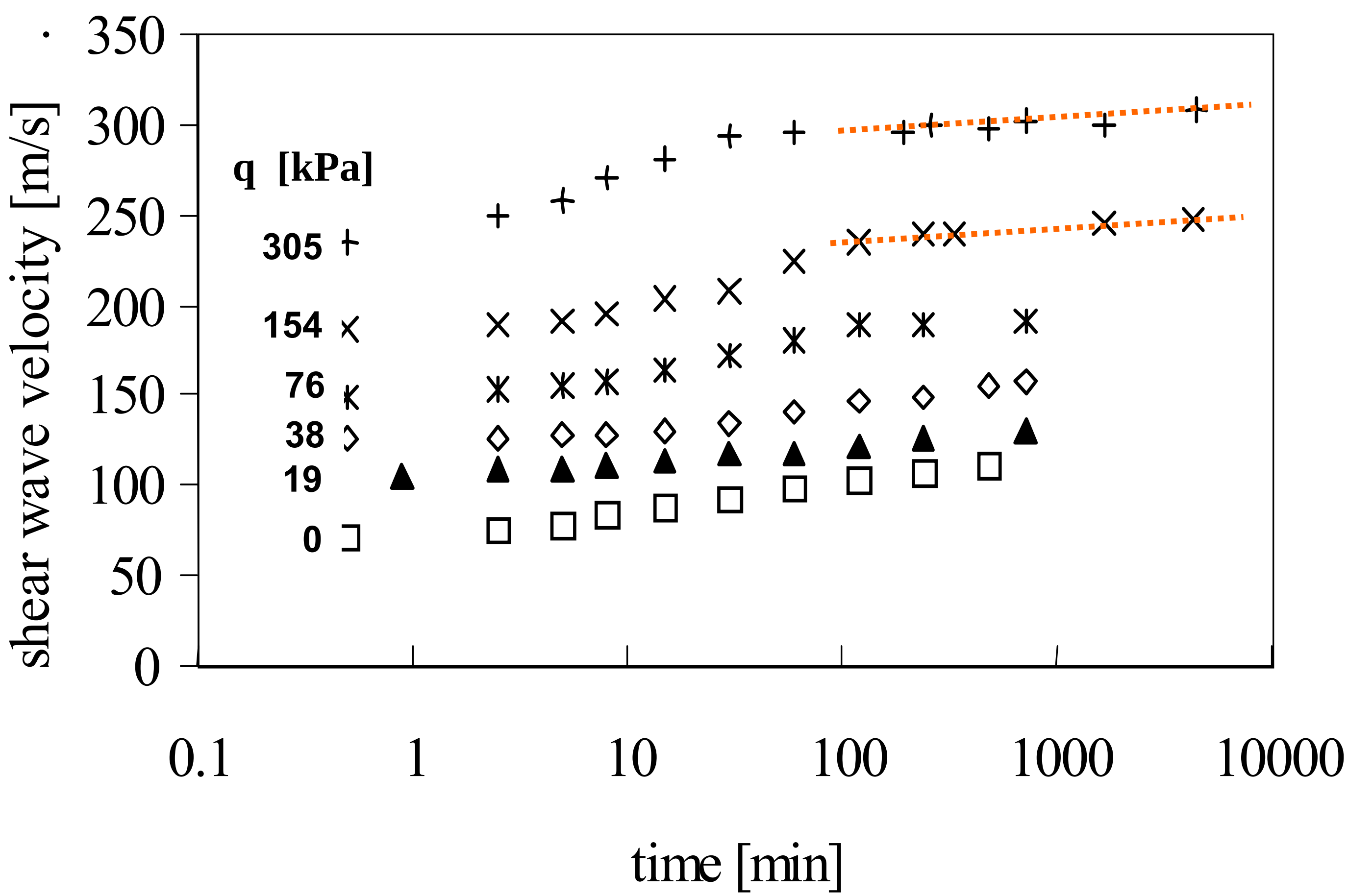


(a)

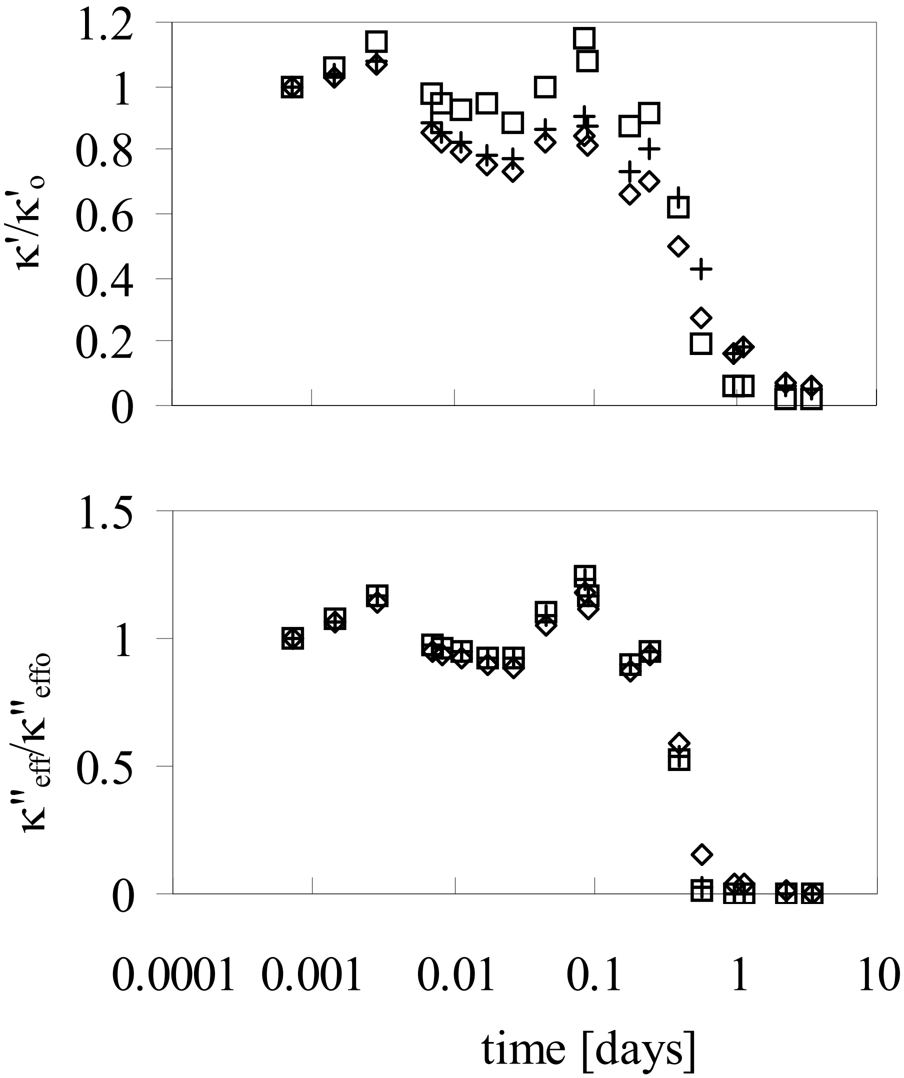


(b)

Pressure diffusion

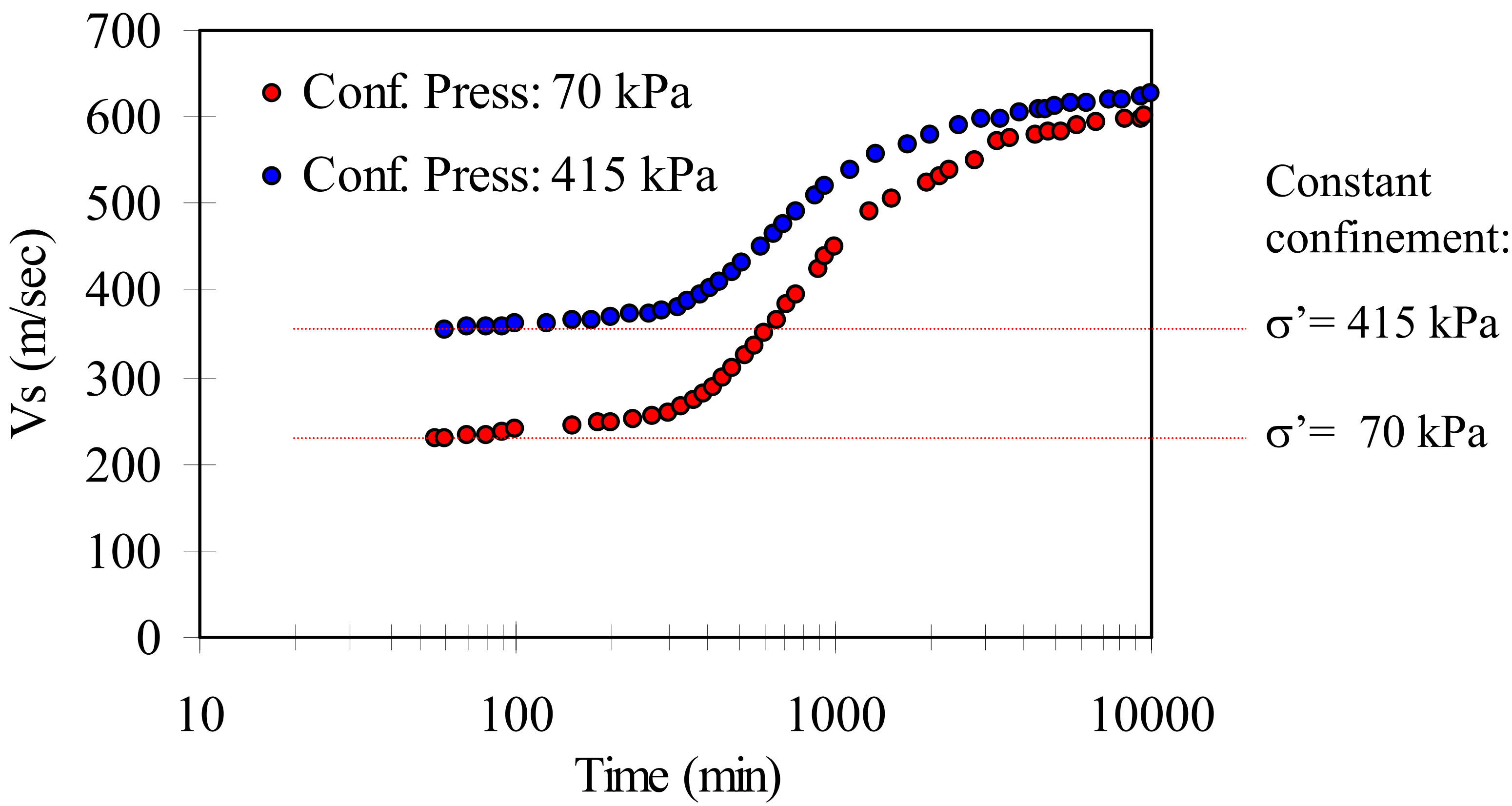


Cementation *(bentonite-cement)*



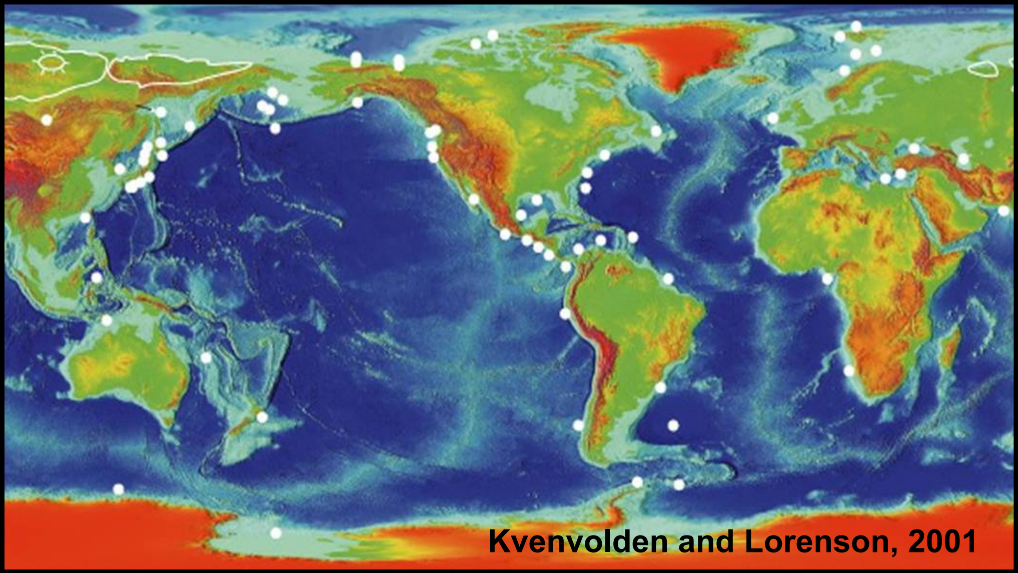
M. Fam

Cementation *(sand-cement)*

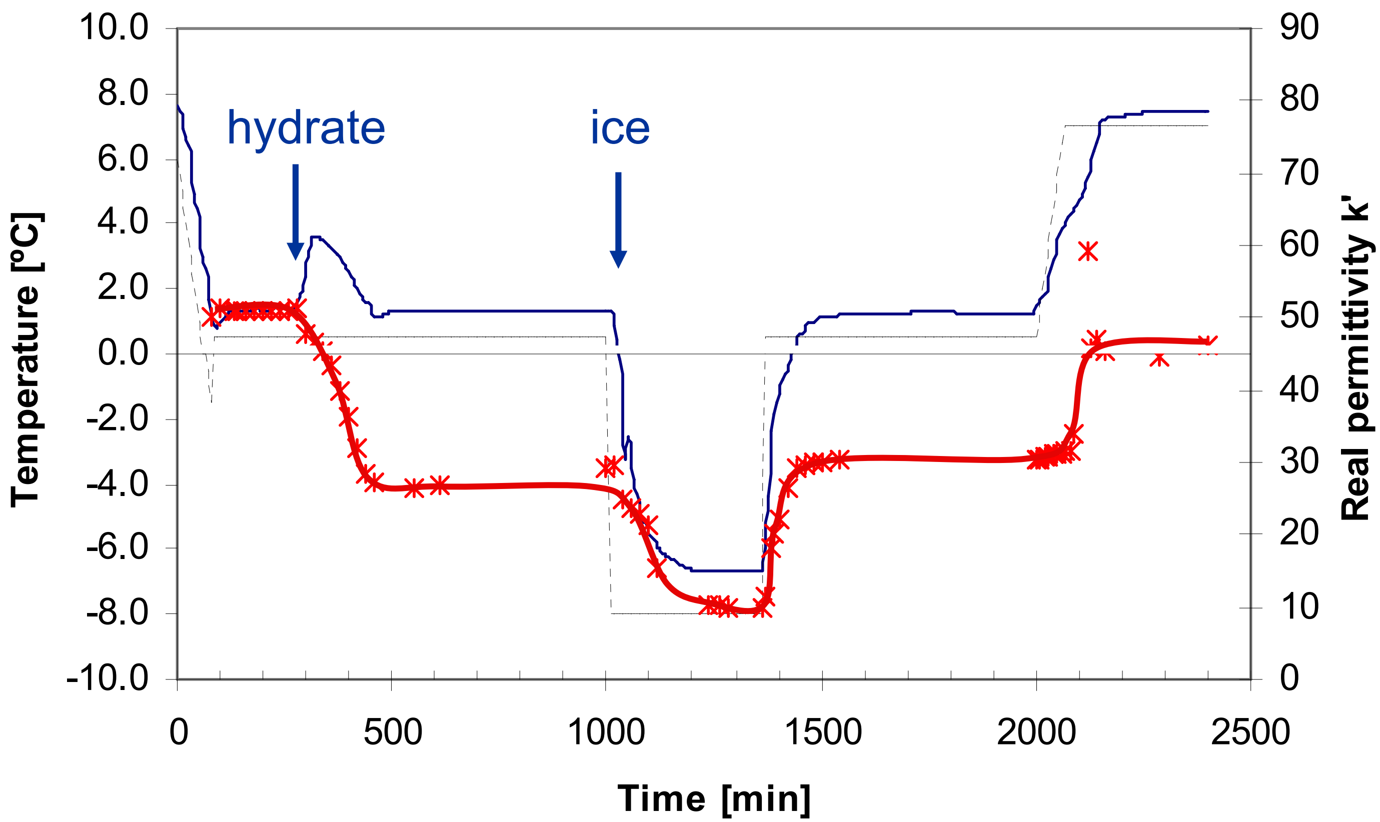


A. Fernandez

Gas hydrates

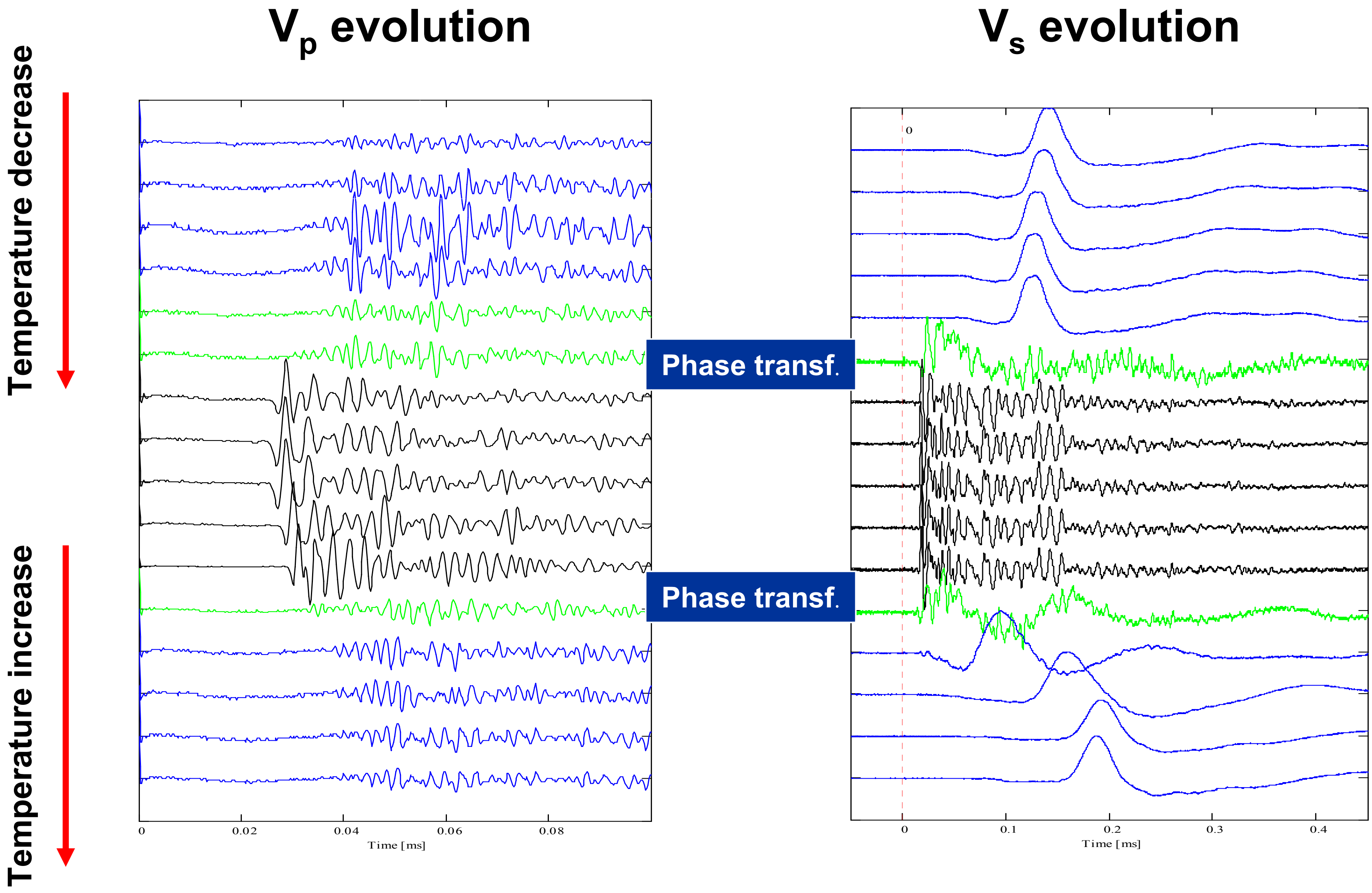


Real Permittivity (Kaolinite + THF + H_2O)



F. Francisca

Elastic waves



TS. Yun

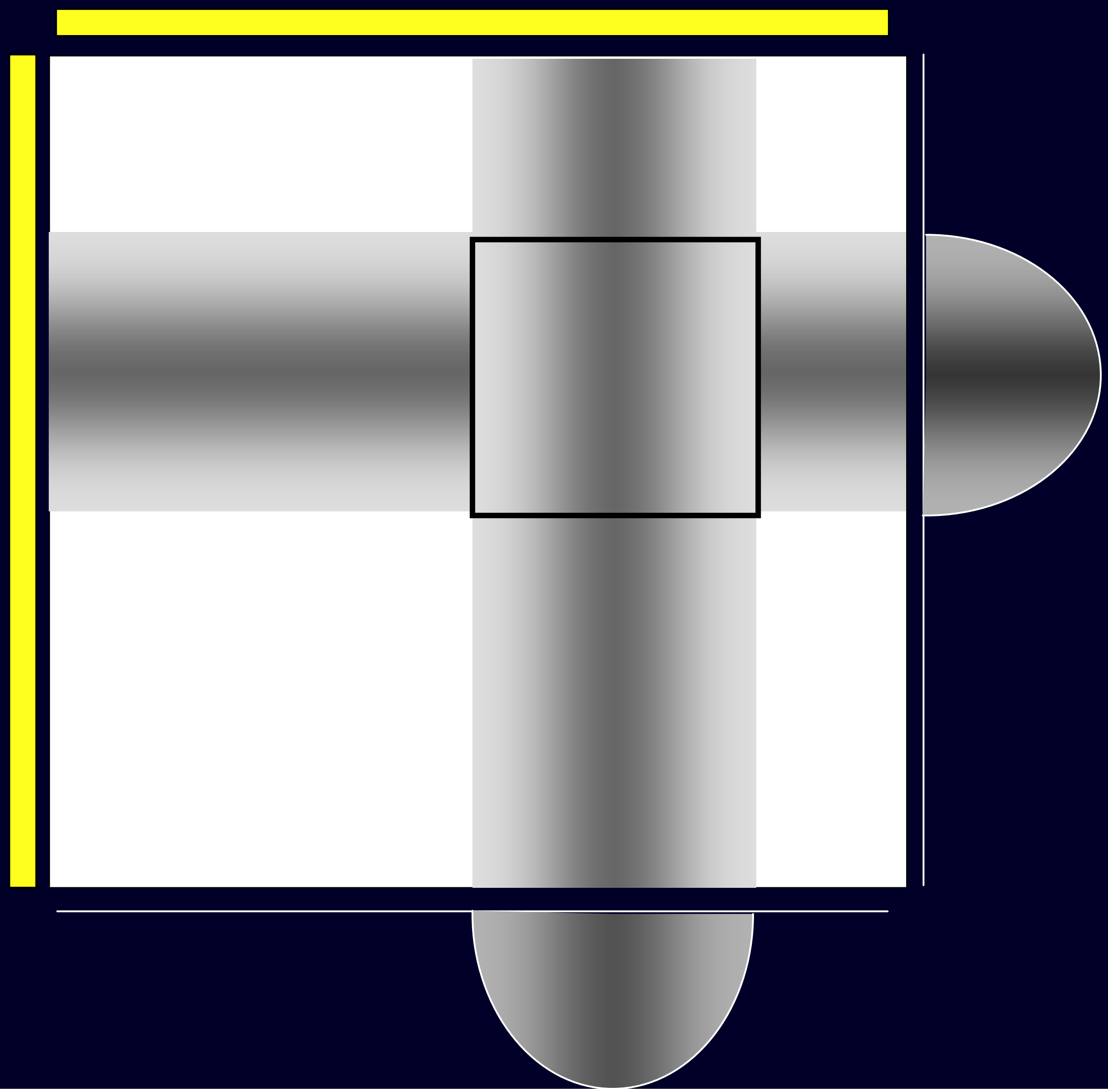
Penetration-based Geophysical Systems

SV Source
(Fernandez)

3D Geophone
(Stokoe – UT)

Conductivity tip

Boundary measurements - Tomography



closing thoughts

Measurement κ^* σ μ^*

TDR signature = input * (geometry AND spatially varying material)

Better measurement interpretation

Inversion: caution… follow Ockham's criterion

Inherent: insertion volume change

Consider non-intrusive implementation

Complementary information

Electromagnetic	**&**	**elastic waves**
Small perturbation	**&**	**large-strain penetration testing**

Wave parameters: relevant to engineering

Laboratory and field

Wide range of geotechnical processes

Boundary measurements: invert for internal conditions

Thank You