

TDR 2006

Purdue University

Plenary Lecture: Innovations, Challenges, and Future Opportunities

J. Carlos Santamarina

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Innovations, Challenges, and Future Opportunities

J. Carlos Santamarina
Georgia Institute of Technology

electromagnetic waves

Maxwell's Equations

Gauss' Law of Electricity

$$\int_{\text{surf}} \epsilon \mathbf{E} \cdot d\mathbf{s} = \int_{\text{vol}} \rho_v^{<\text{free}>} dv$$

$$\nabla \cdot \mathbf{E} = \frac{1}{\epsilon} \rho_v^{<\text{free}>}$$

Gauss' Law of Magnetism

$$\int_{\text{surf}} \mathbf{H} \cdot d\mathbf{s} = 0$$

$$\nabla \cdot \mathbf{H} = 0$$

Faraday's Law of Induction

$$\int_{\text{loop}} \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt} \int_{\text{surf}} \mu \mathbf{H} \cdot d\mathbf{s}$$

$$\nabla \times \mathbf{E} = -\mu \frac{d\mathbf{H}}{dt}$$

Ampere-Maxwell's Law

$$\int_{\text{loop}} \mathbf{H} \cdot d\mathbf{l} = \int_{\text{surf}} \mathbf{J} \cdot d\mathbf{s} + \frac{d}{dt} \int_{\text{surf}} \epsilon \mathbf{E} \cdot d\mathbf{s}$$

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \epsilon \frac{d\mathbf{E}}{dt}$$

Wave Equation

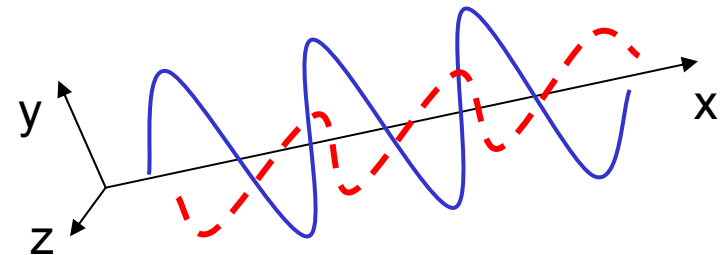
$$\nabla^2 \mathbf{E} = \mu^* \sigma \frac{\partial \mathbf{E}}{\partial t} + \mu^* \varepsilon^* \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

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

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

non-ferromagnetic / dielectric

$$\mu^* = \mu_0 \quad \varepsilon^* = \varepsilon' \quad \sigma = 0$$

$$V_{ph} = \frac{c_0}{\sqrt{\varepsilon'/\varepsilon_0}}$$

Attenuation

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

non-ferromagnetic

$$\mu^* = \mu_0 \quad \varepsilon^* = \varepsilon' + j\varepsilon'' \quad \sigma$$

$$\alpha = \frac{\omega \sqrt{\varepsilon'/\varepsilon_0}}{c_0} \sqrt{\frac{1}{2} \left(\sqrt{1 + \tan^2 \delta} - 1 \right)}$$

For 1D propagation

Skin depth

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

Impedance

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

Reflection and Transmission

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

Electromagnetic Parameters

Conductivity

$$\sigma$$

Permittivity

$$\epsilon^* = \epsilon' - j \epsilon''$$

Permeability

$$\mu = \mu' - j \mu''$$

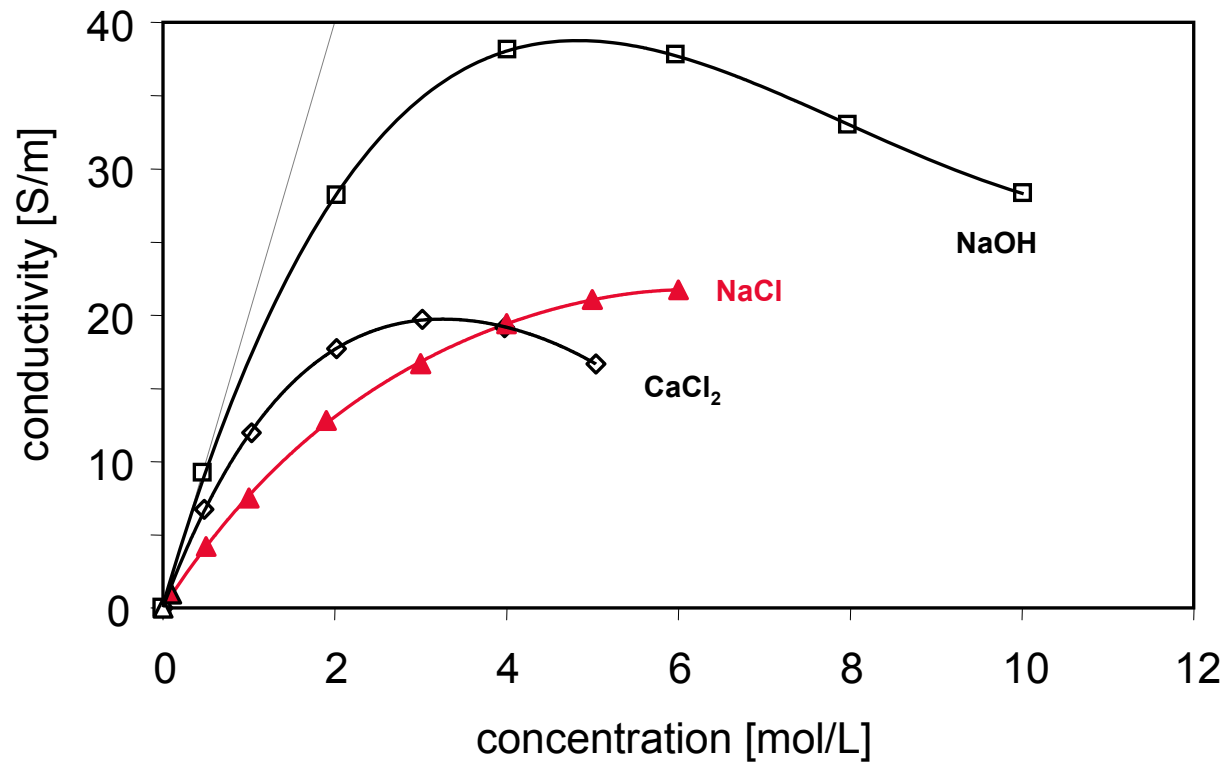
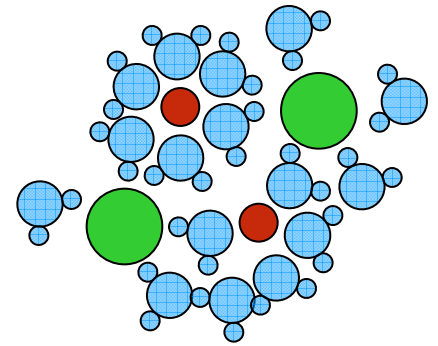
Effective conductivity

$$\sigma_{\text{eff}} = \epsilon'' \omega \mu_r' + (\sigma + \epsilon'' \omega) \mu_r'$$

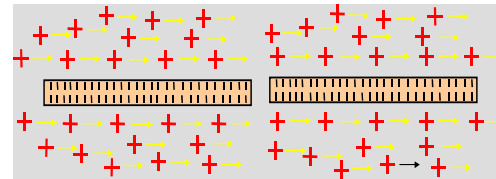
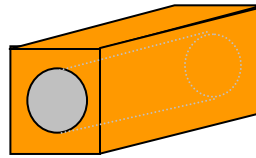
*details and references in
Santamarina, Klein and Fam
Soils and Waves – J. Wiley*

electromagnetic properties

Conductivity - Electrolytes



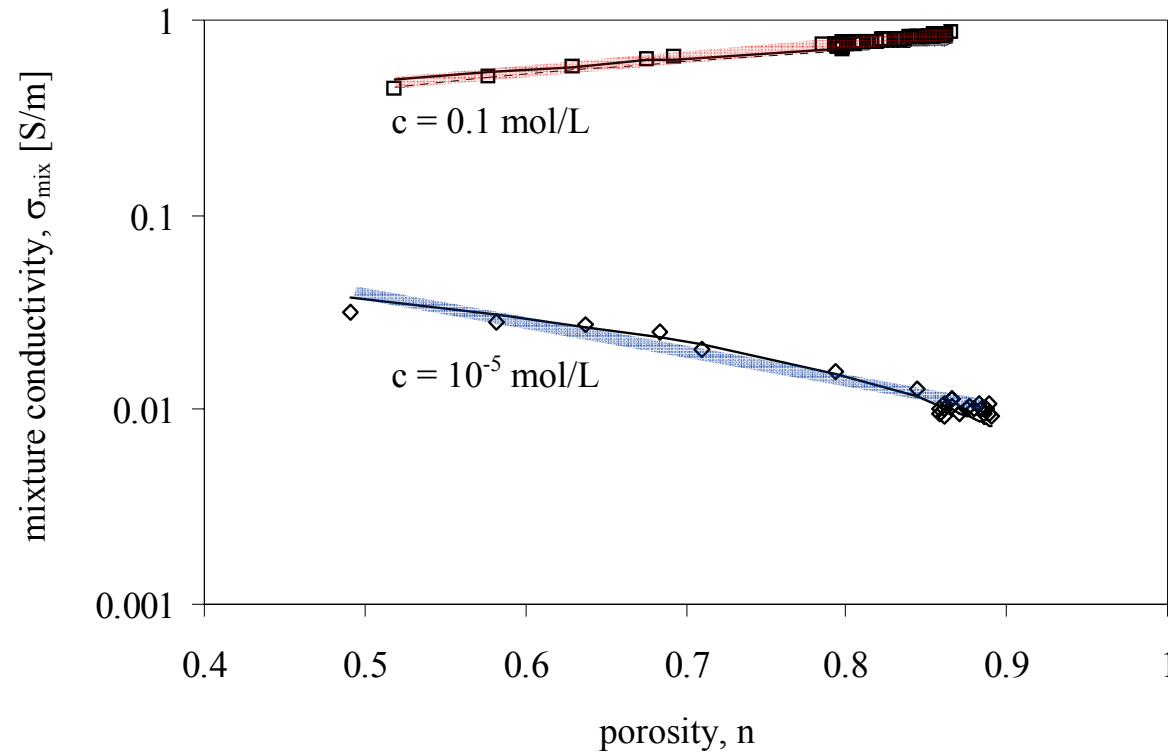
Bulk and Surface Conduction



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

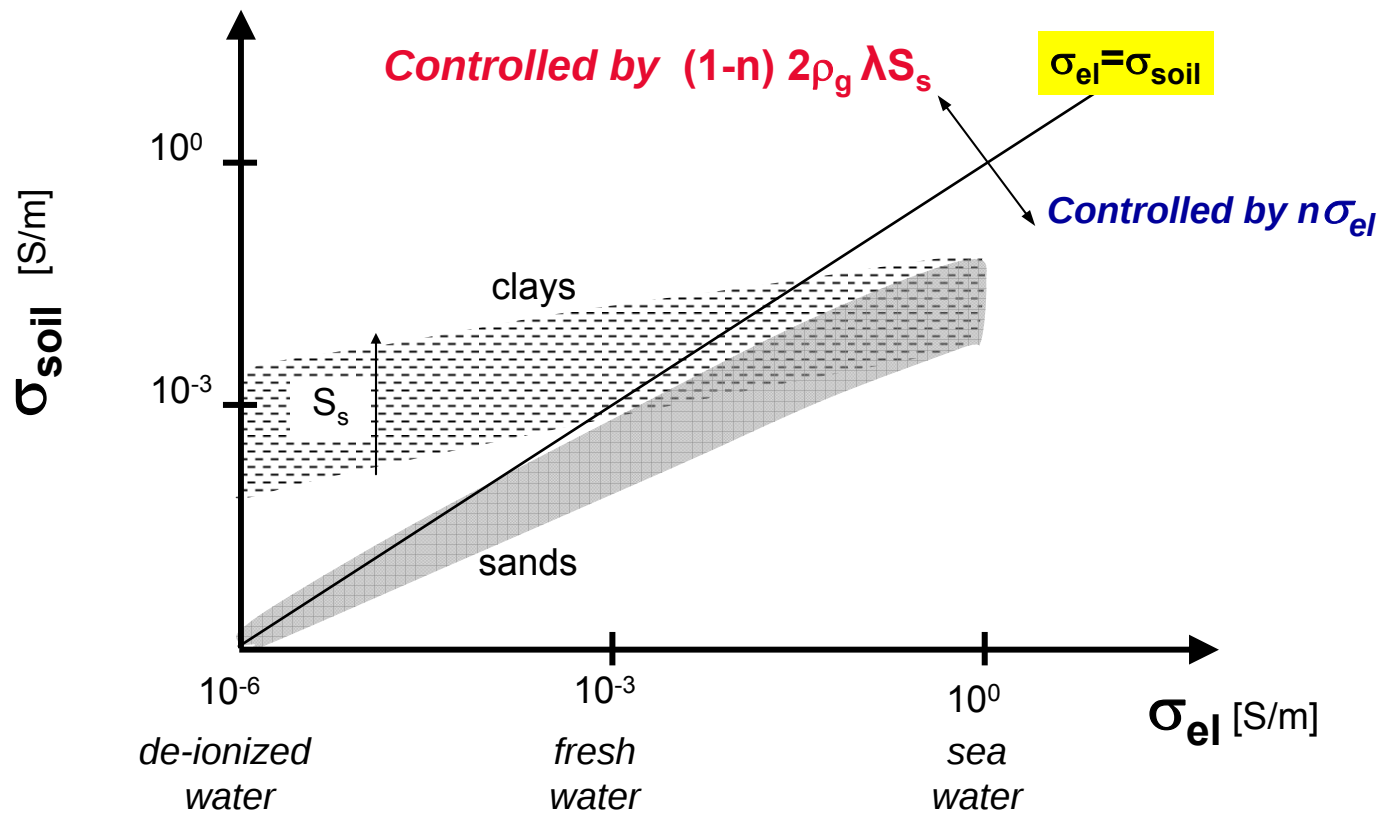
$$\sigma_{\text{soil}} = \alpha n^{\beta} \sigma_{\text{el}} \quad (\text{Archie})$$

Conductivity: Archie?

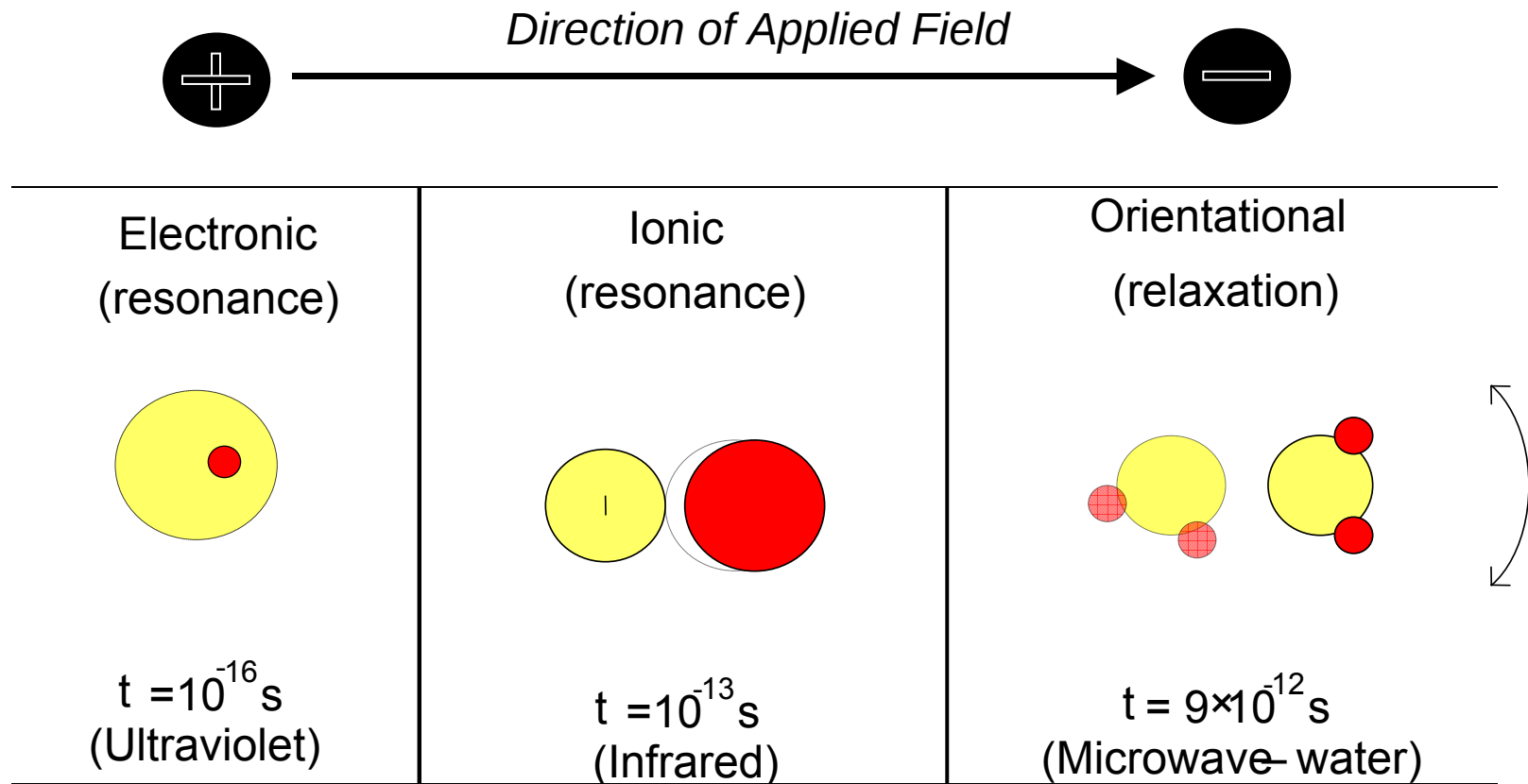


$$\sigma_{\text{soil}} = n \sigma_{\text{el}} + (1-n) 2\rho_g \lambda S_a$$

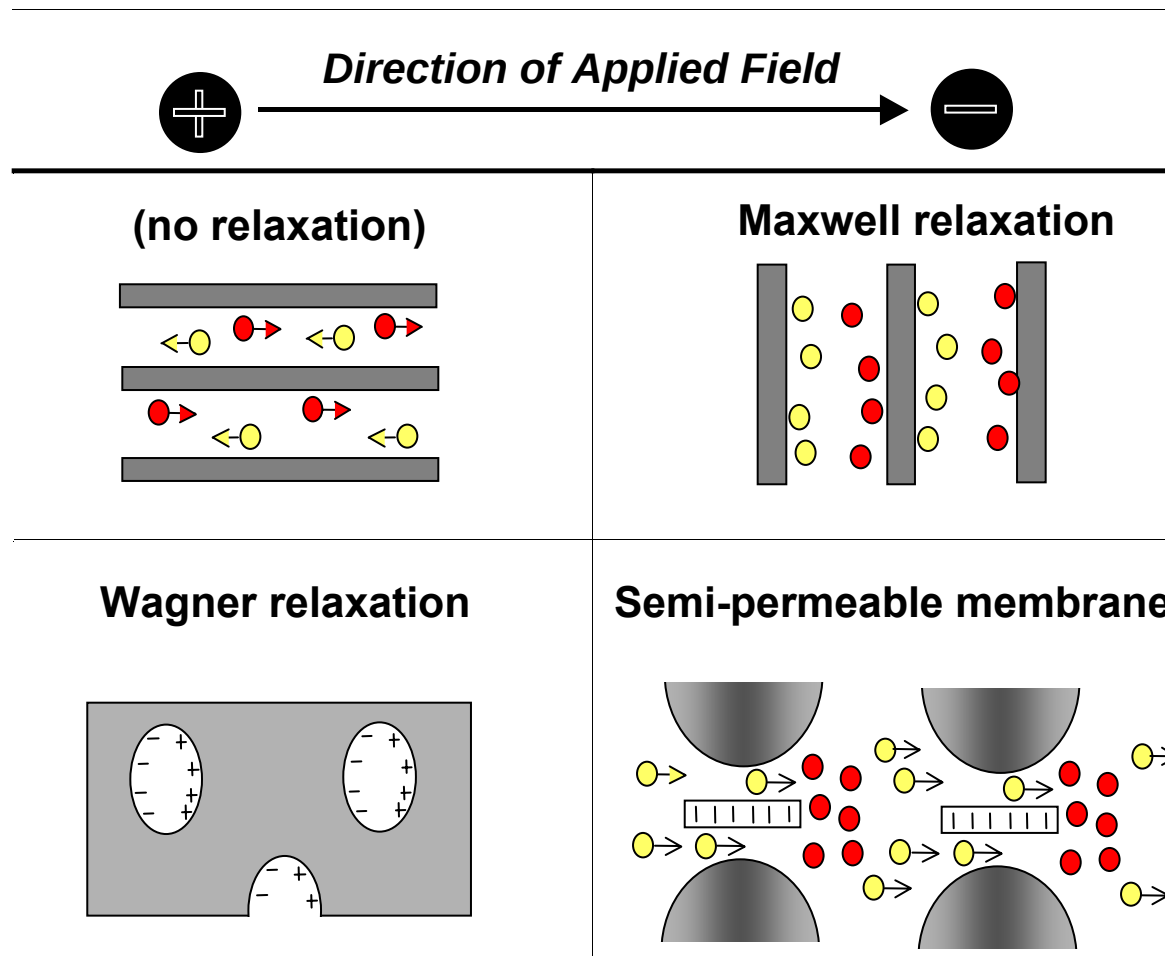
Conductivity - Summary



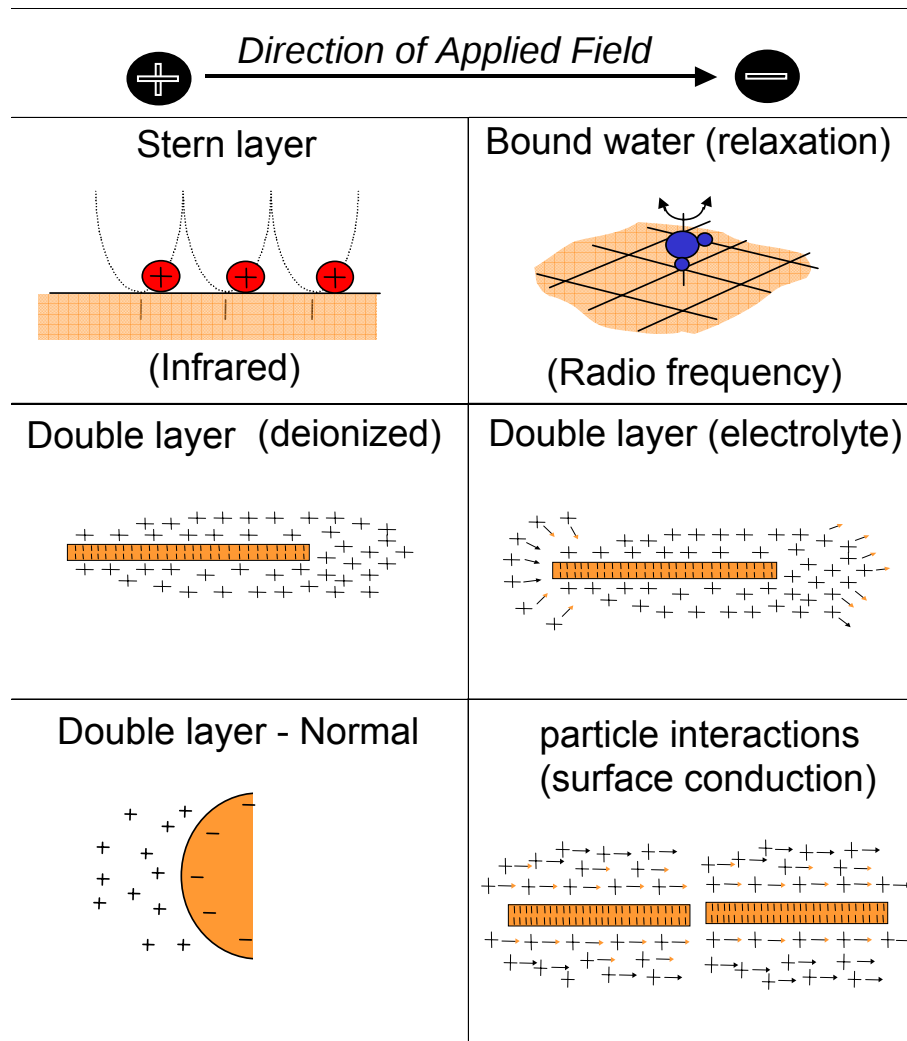
Polarization – Single phase



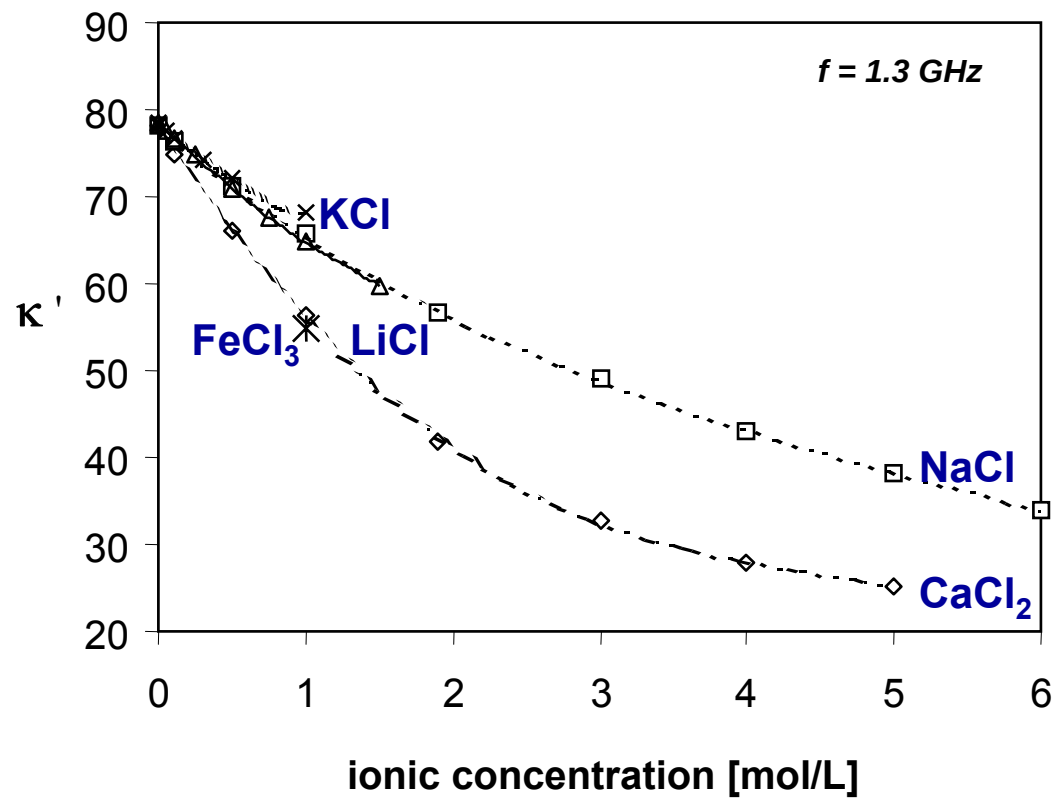
Two-phase media - Spatial polarization



Double layer effects

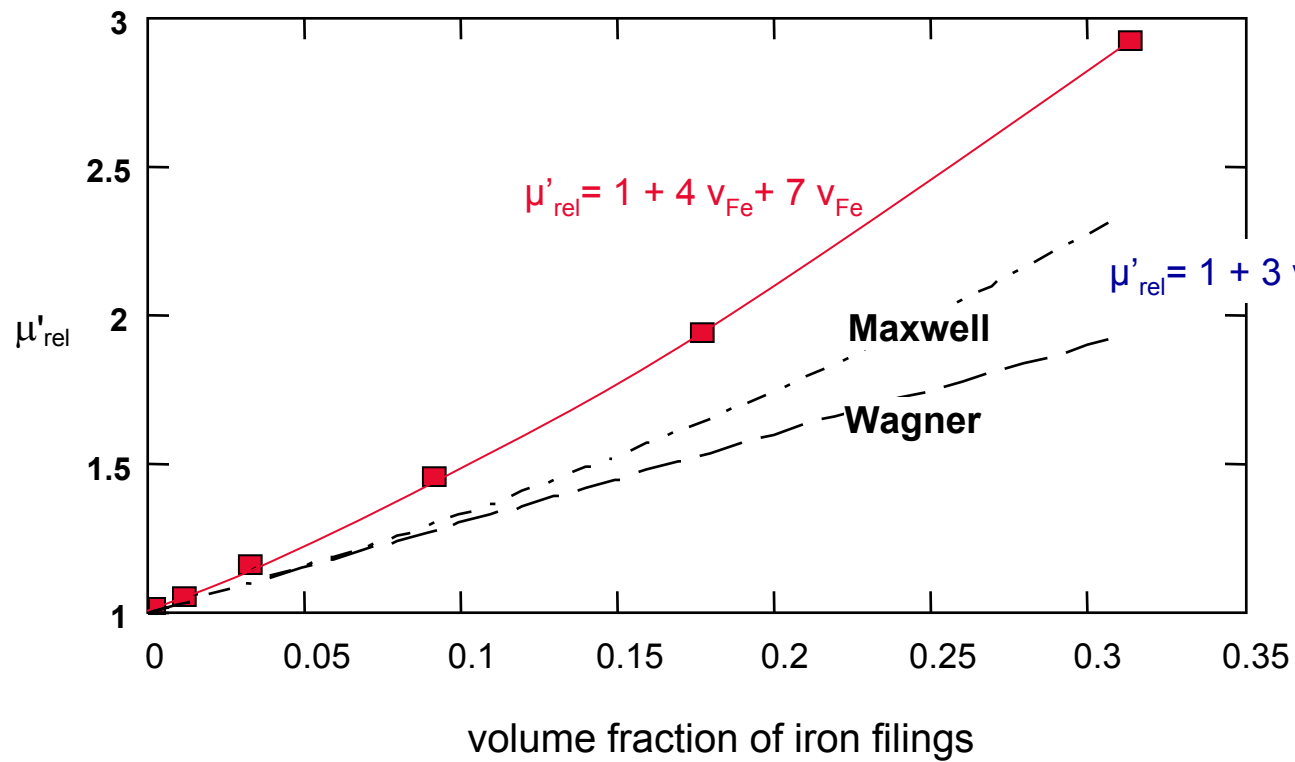


Water-Ion Interaction

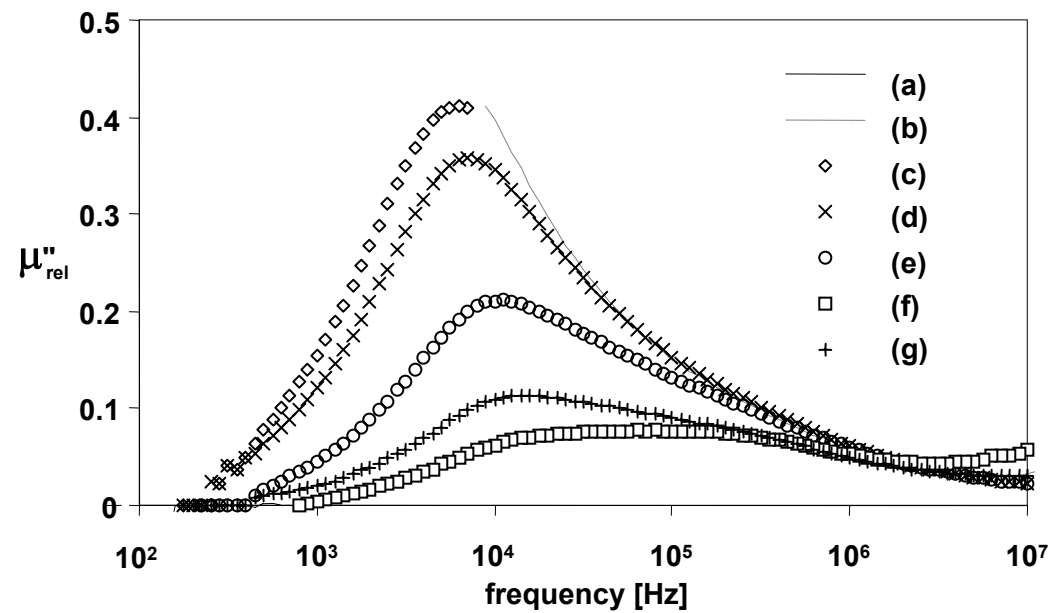
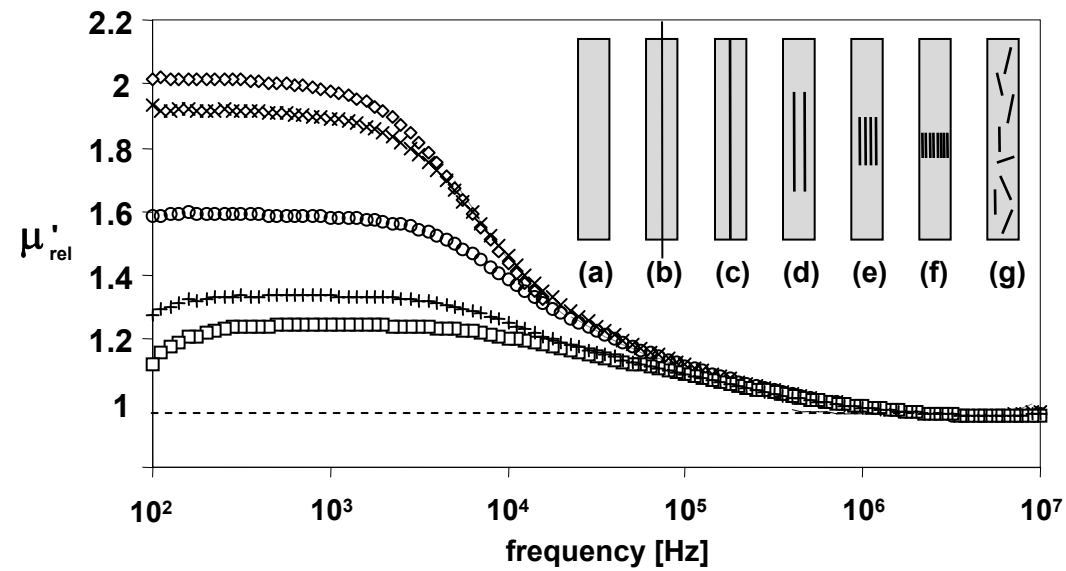


Permeability

iron fillings in kaolinite – $f = 10$ kHz



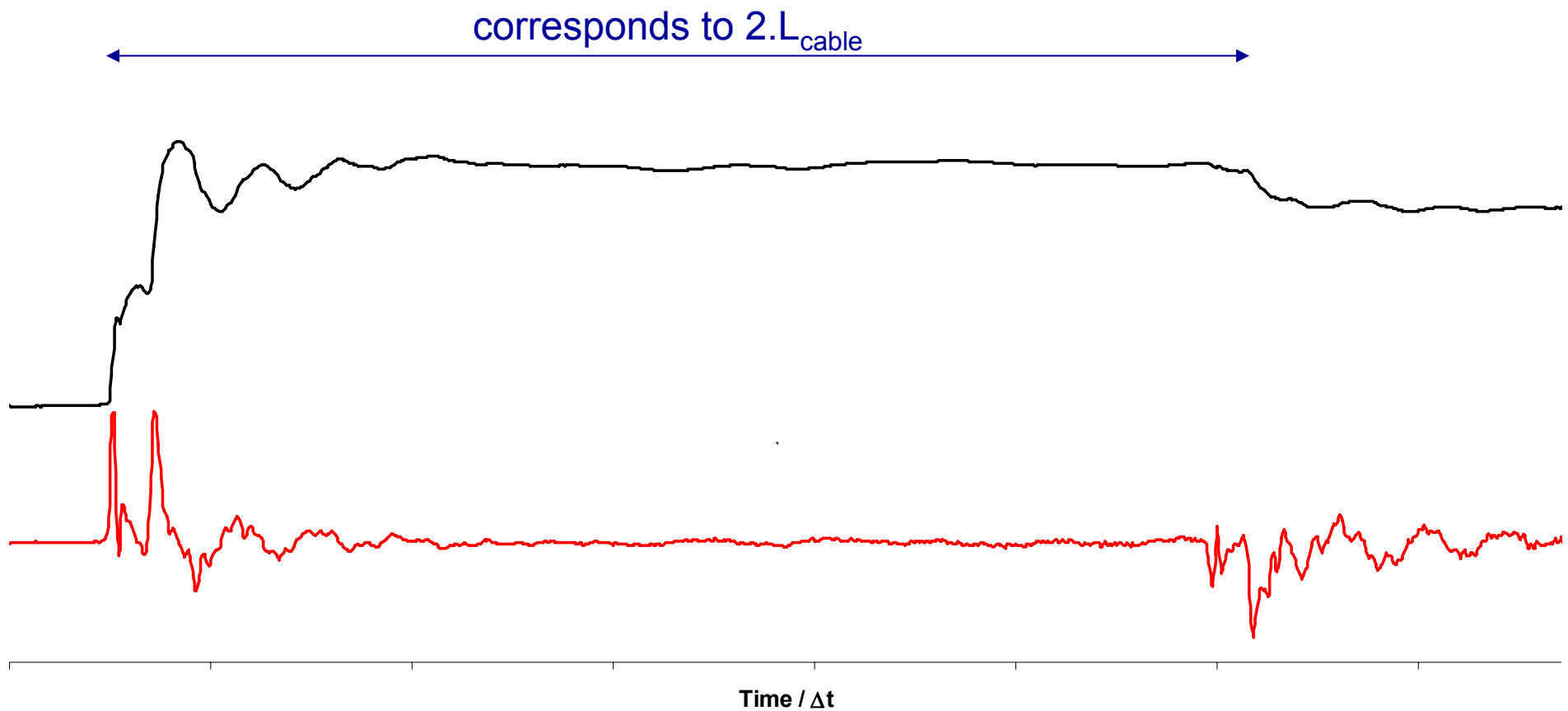
iron in kaolinite



All data by Dante Fratta (U. Wisconsin)

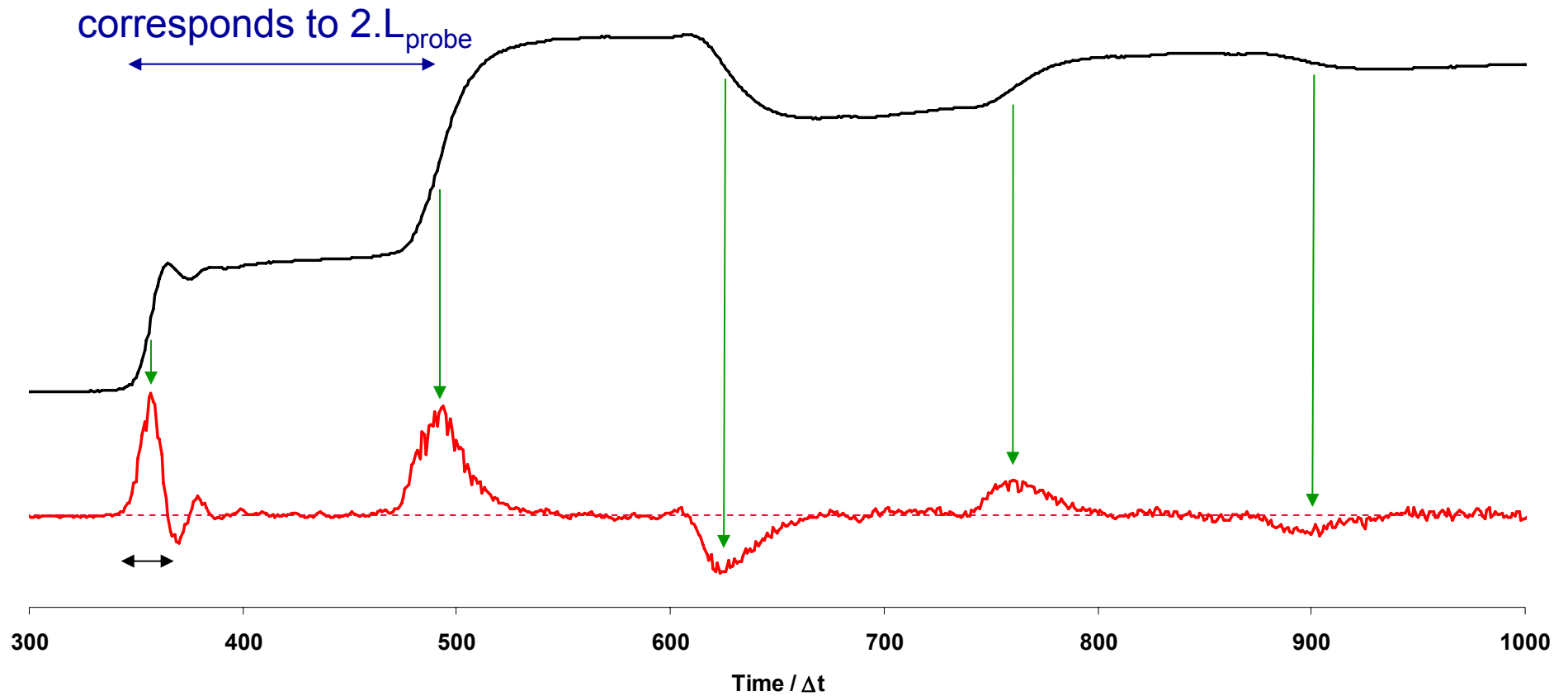
TDR measurements

The Cable



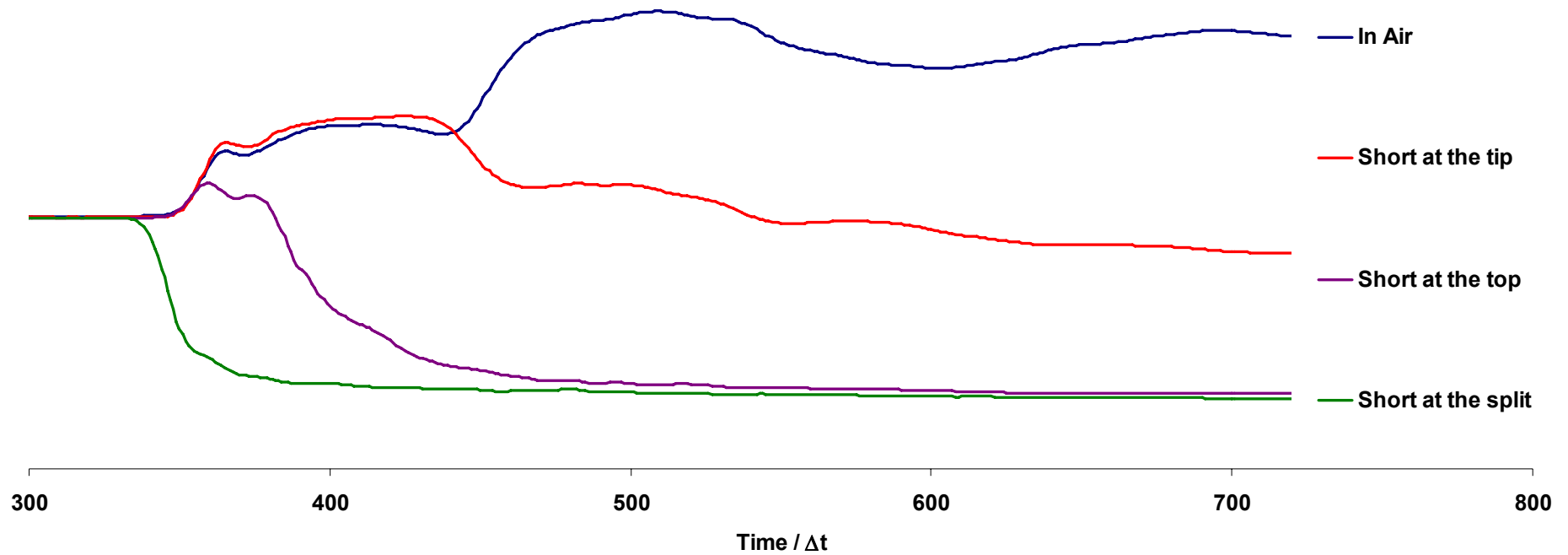
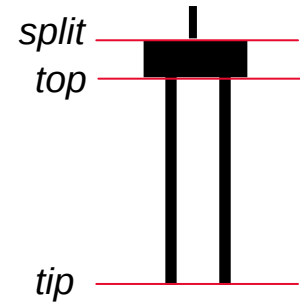
*the probe = complex end-reflector
signal changed sign at equipment*

The Probe



*$f \sim 1$ to 3 GHz
dispersion
multiples*

Short

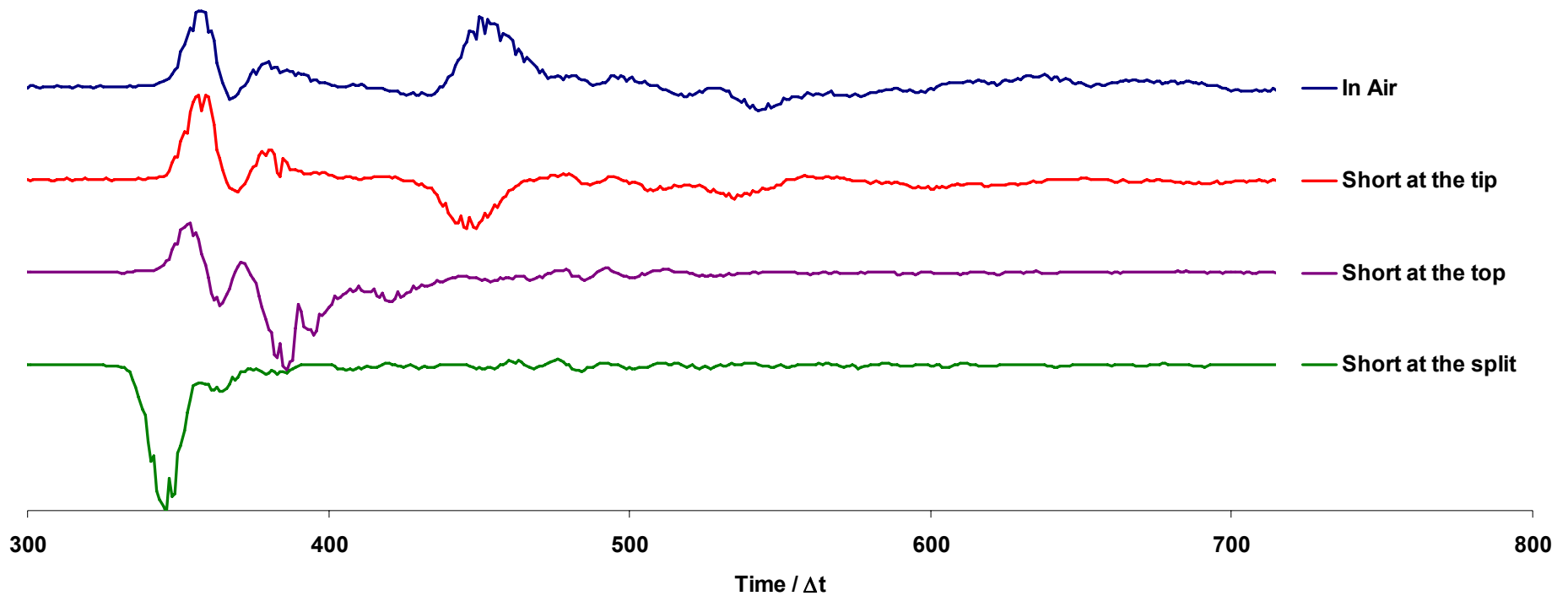
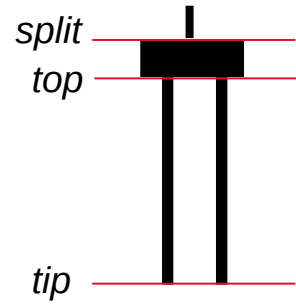


where is zero-time?

composite reflection at top

open and short tip impedance

Short

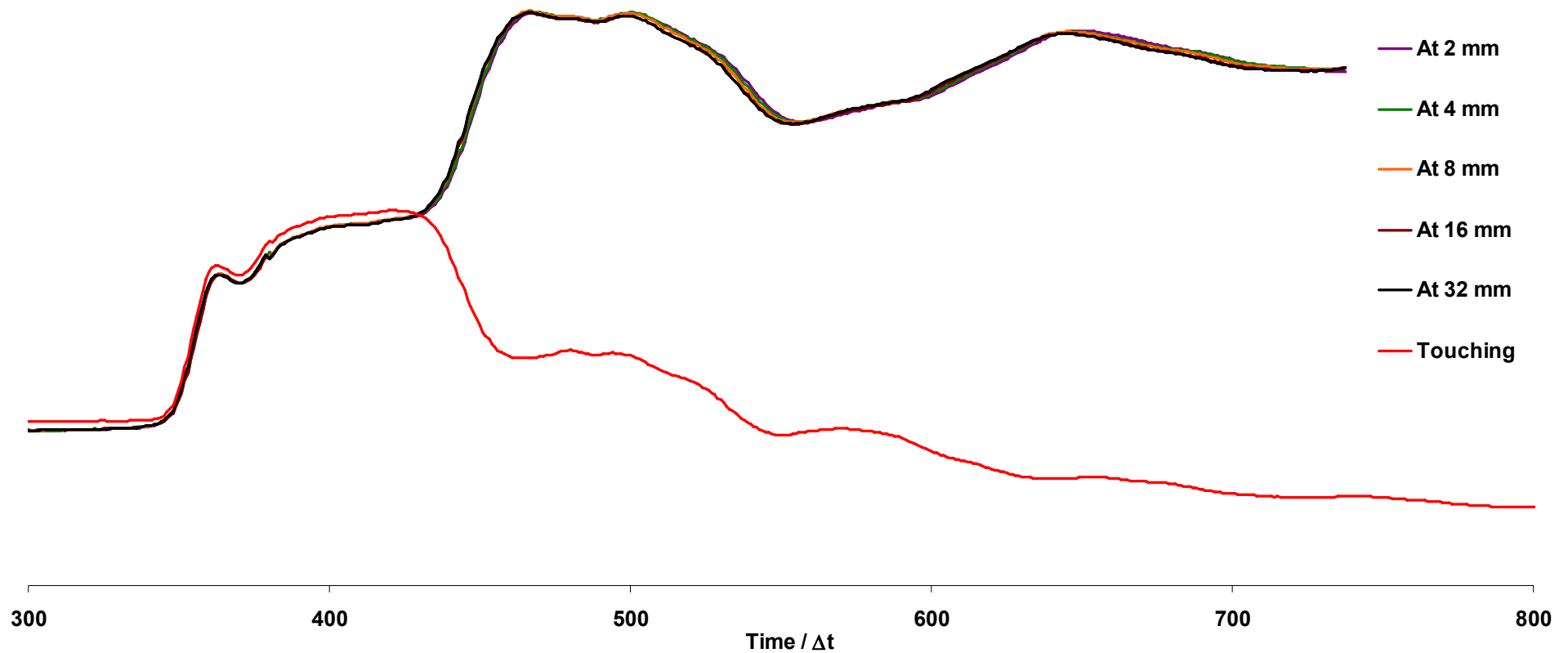


where is zero-time?

composite reflection at top

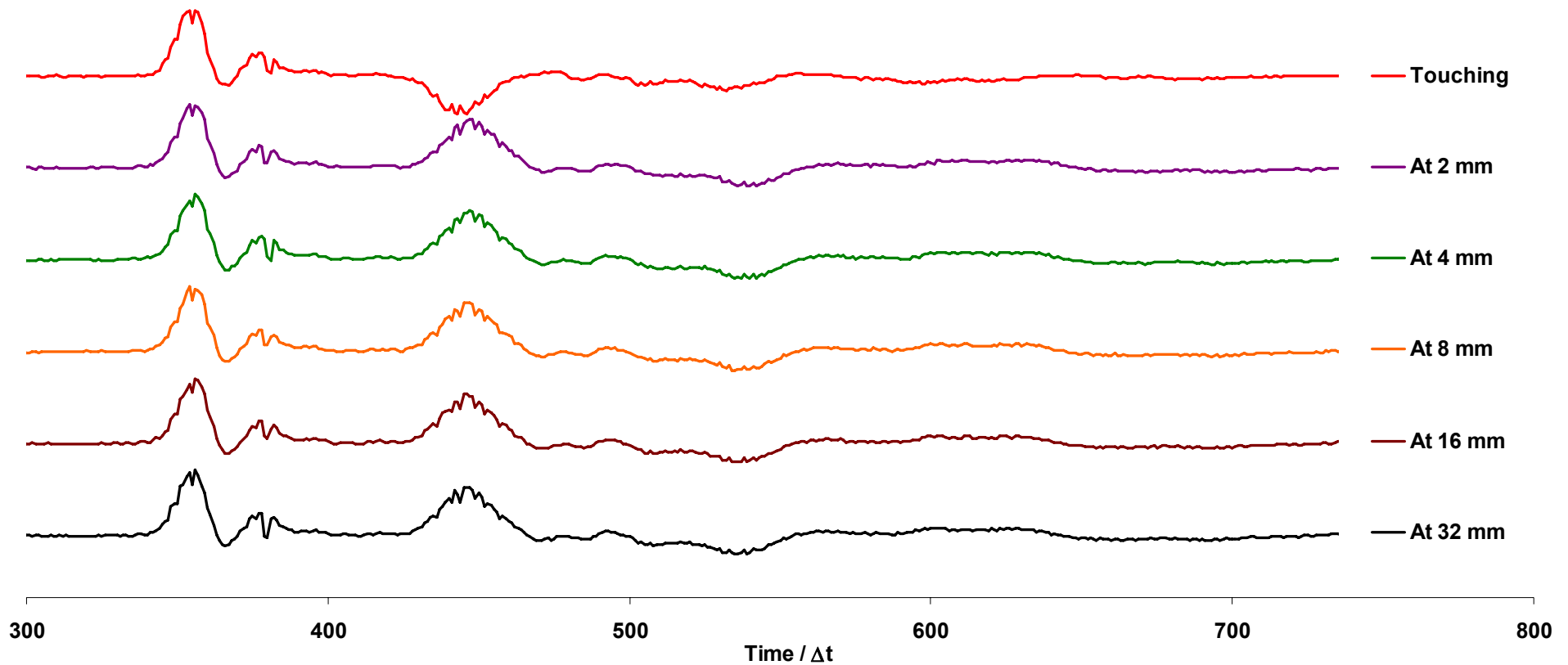
open and short tip impedance

Boundaries: Normal Plate



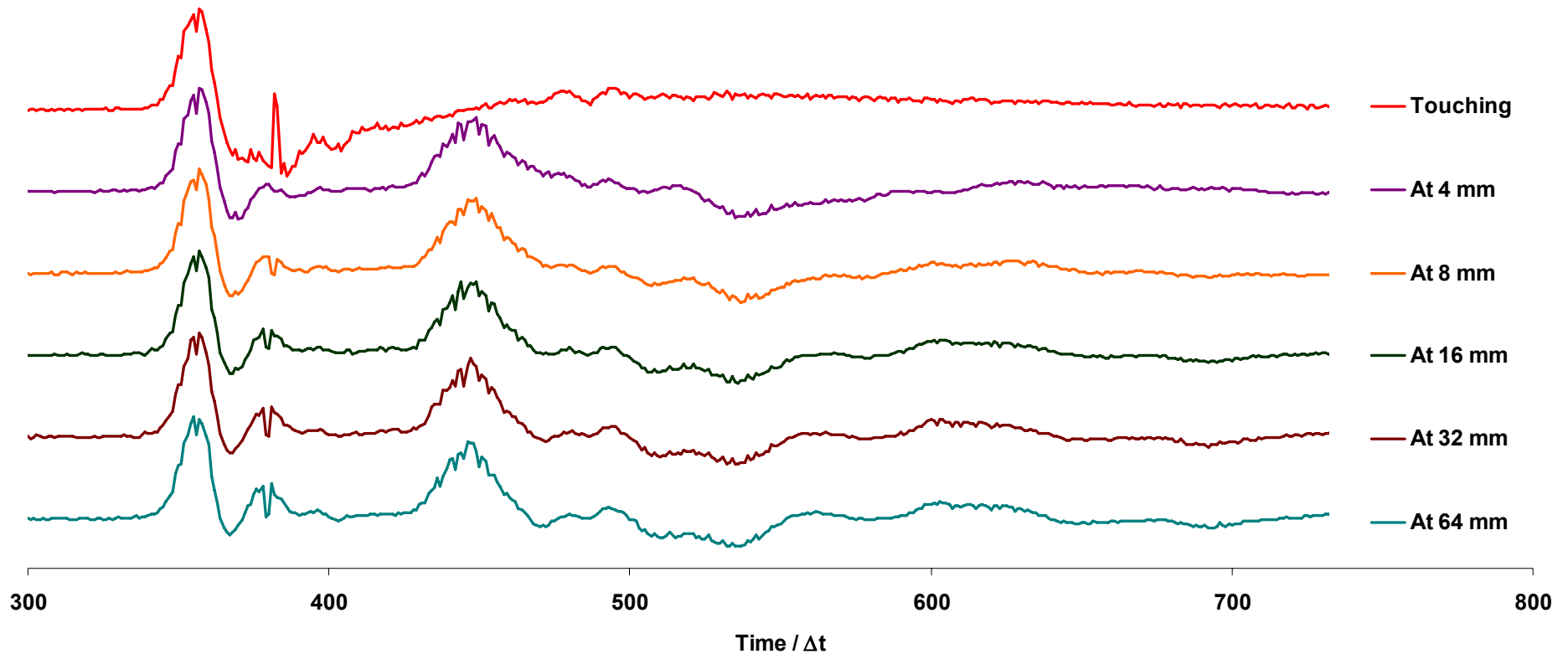
does not see ahead of tip

Boundaries: Normal Plate



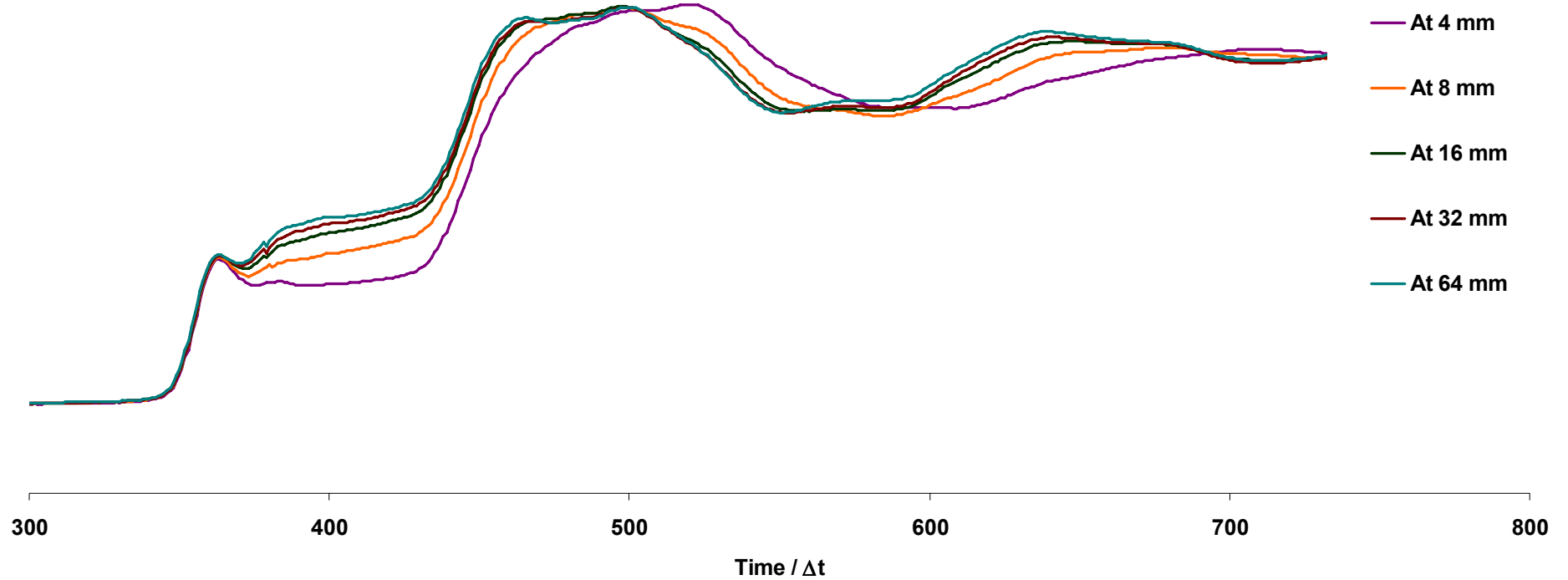
does not see ahead of tip

Boundaries: Parallel Plate



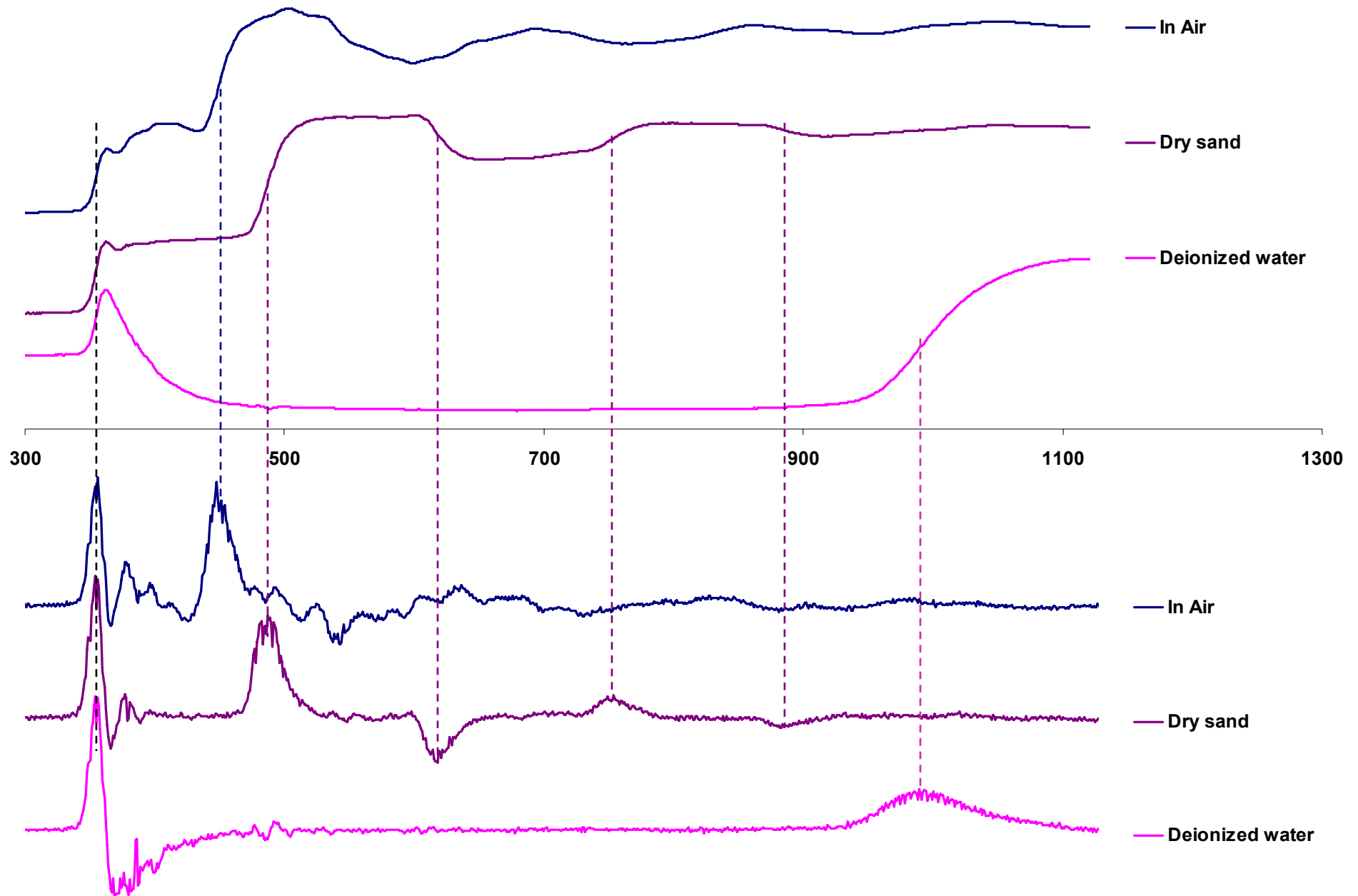
does not feel outside inter-rod ?

Boundaries: Parallel Plate



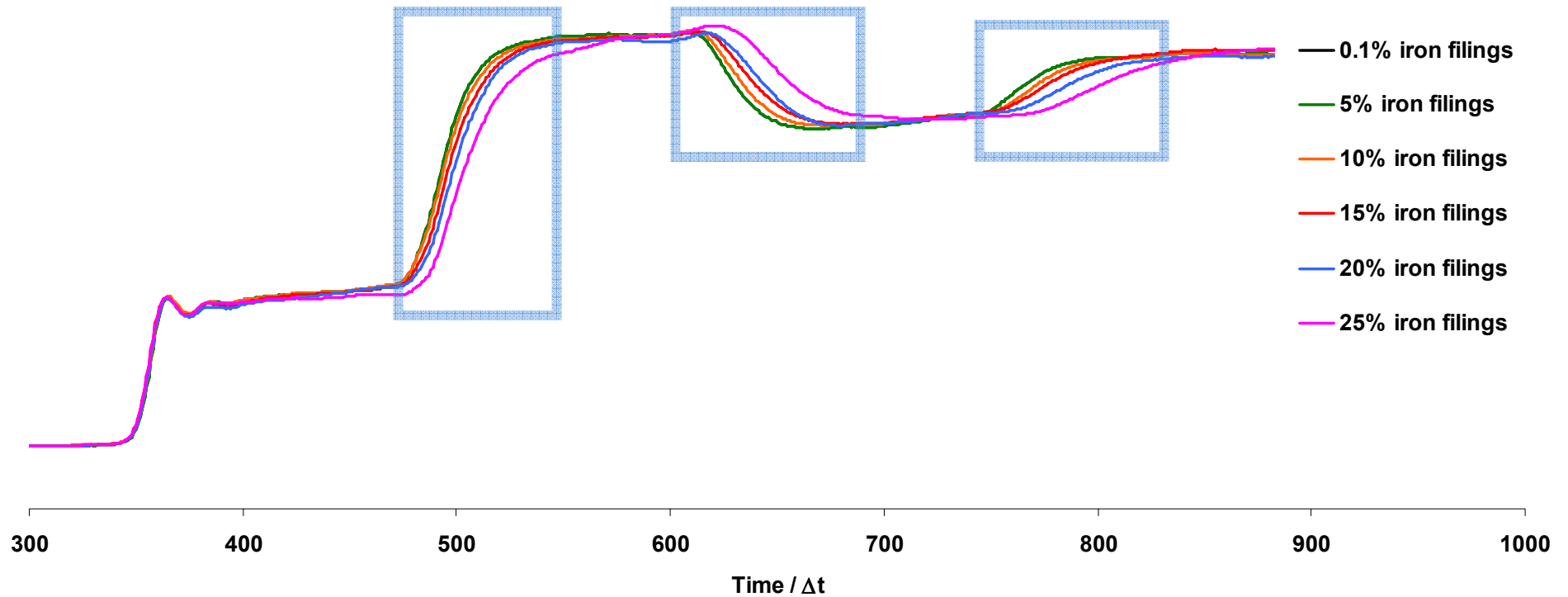
H-field effect!

Permittivity



Permeability

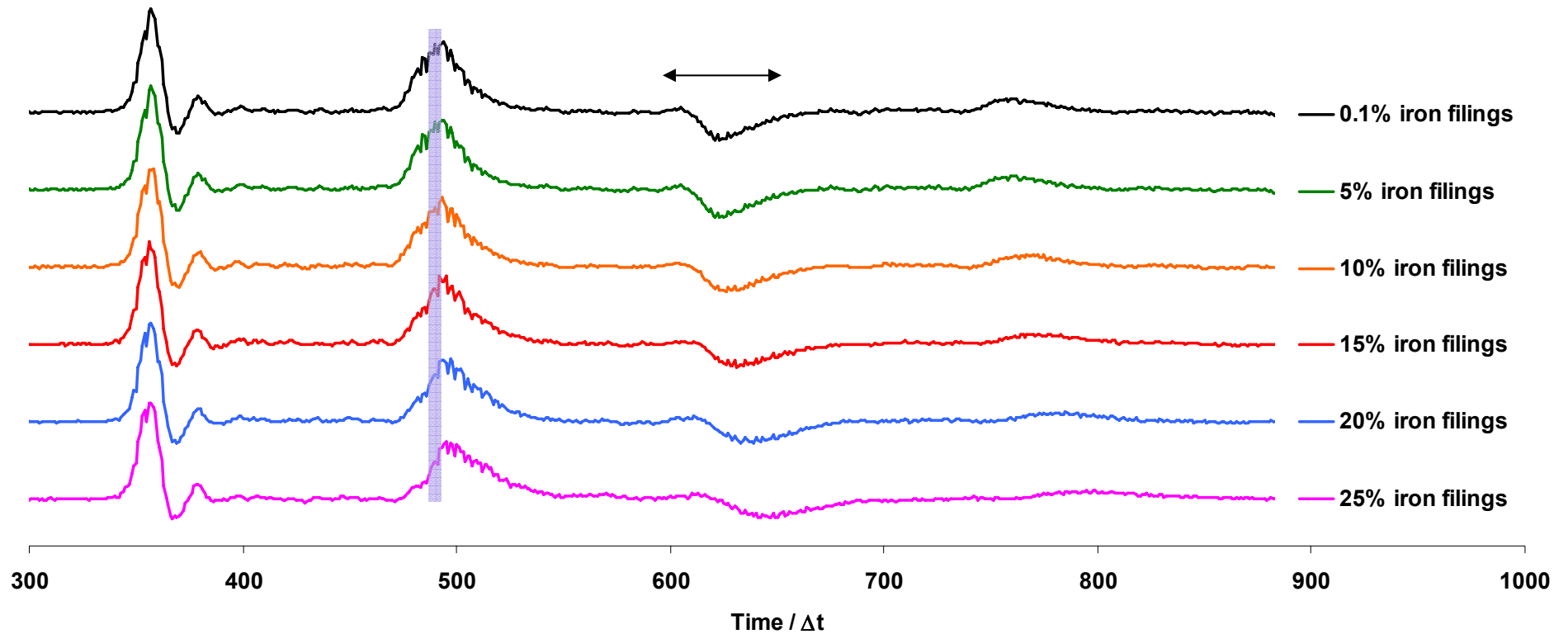
Sand +



expect minor effect

Permeability

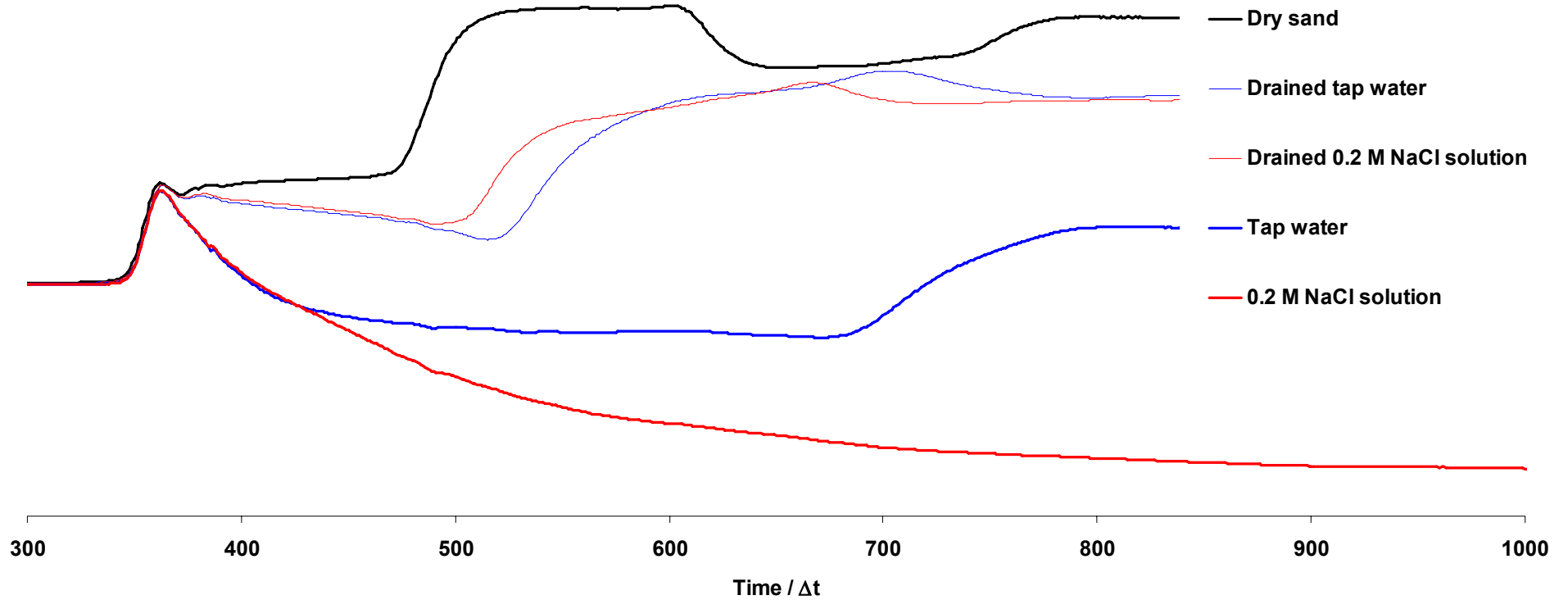
Sand +



expect minor effect

Conductivity

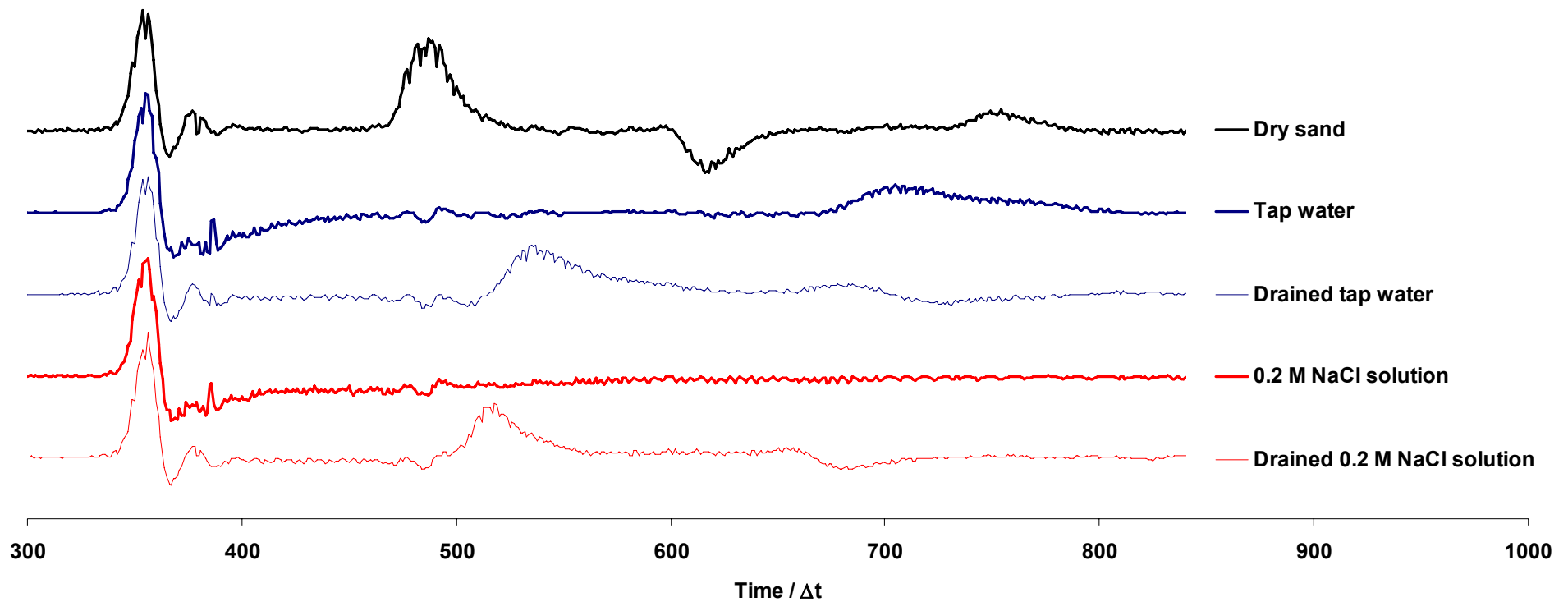
Sand



good assessment of conductivity

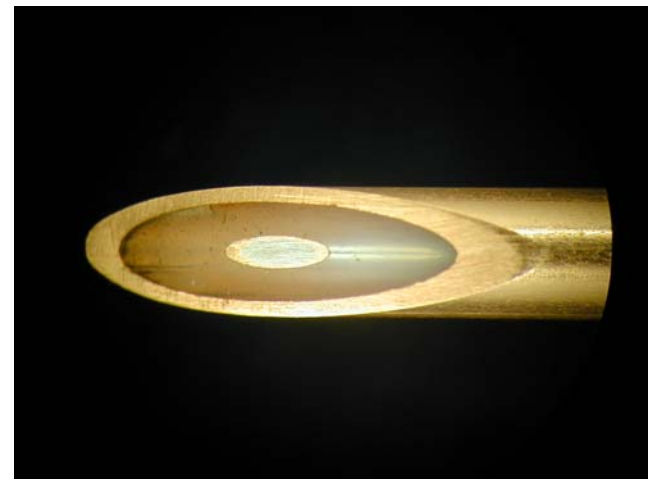
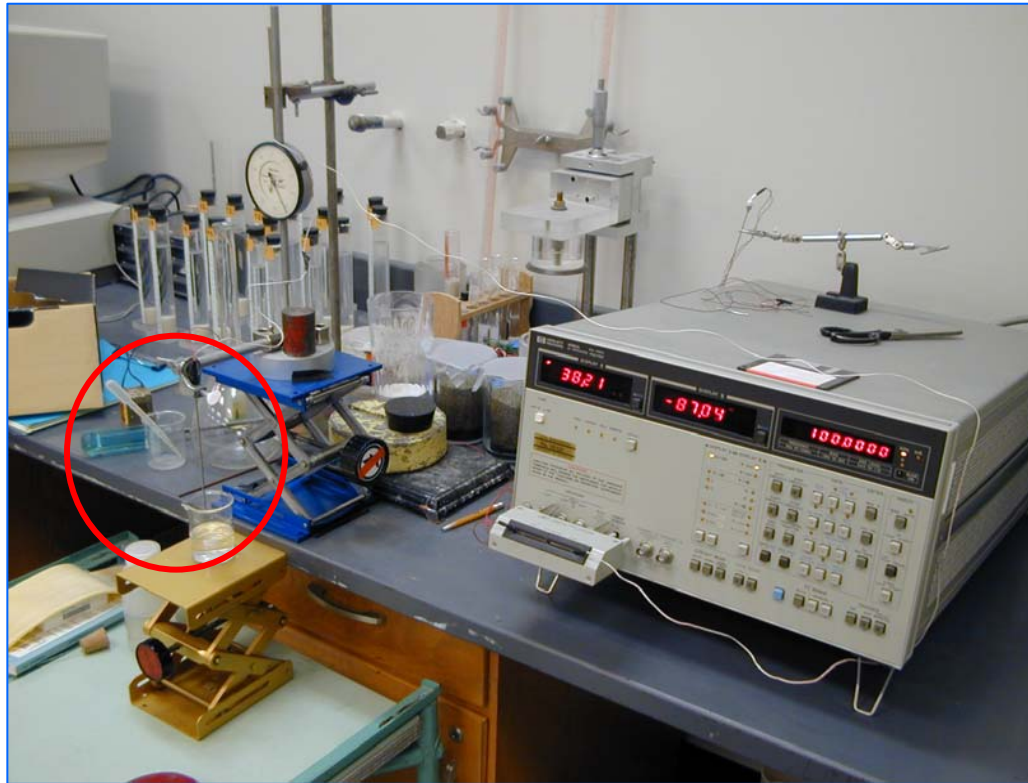
Conductivity

Sand



*recall skin depth
may not see tip reflection*

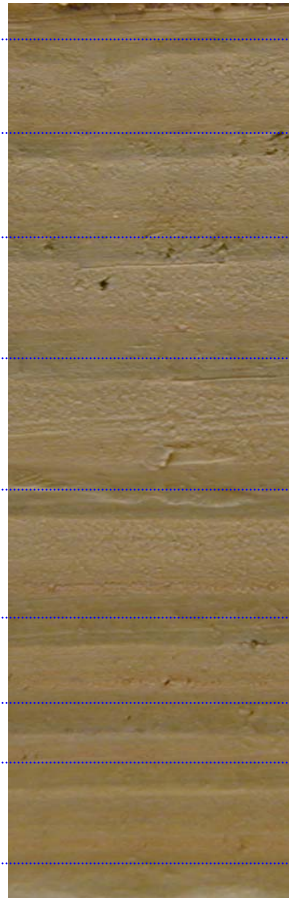
Heterogeneity – Layering



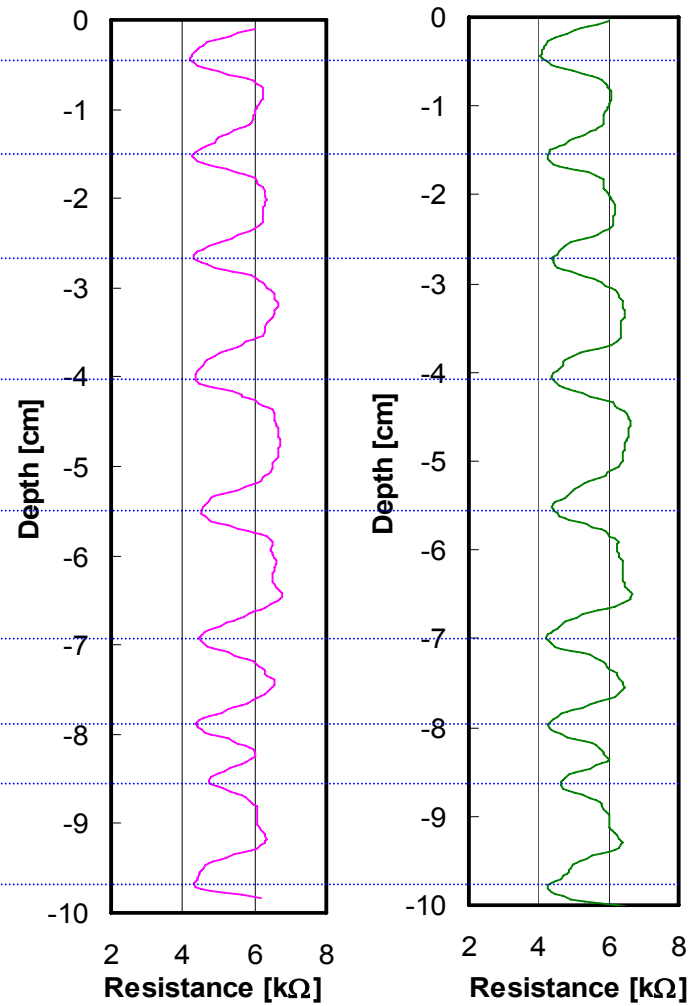
Varved Clay



X-Ray

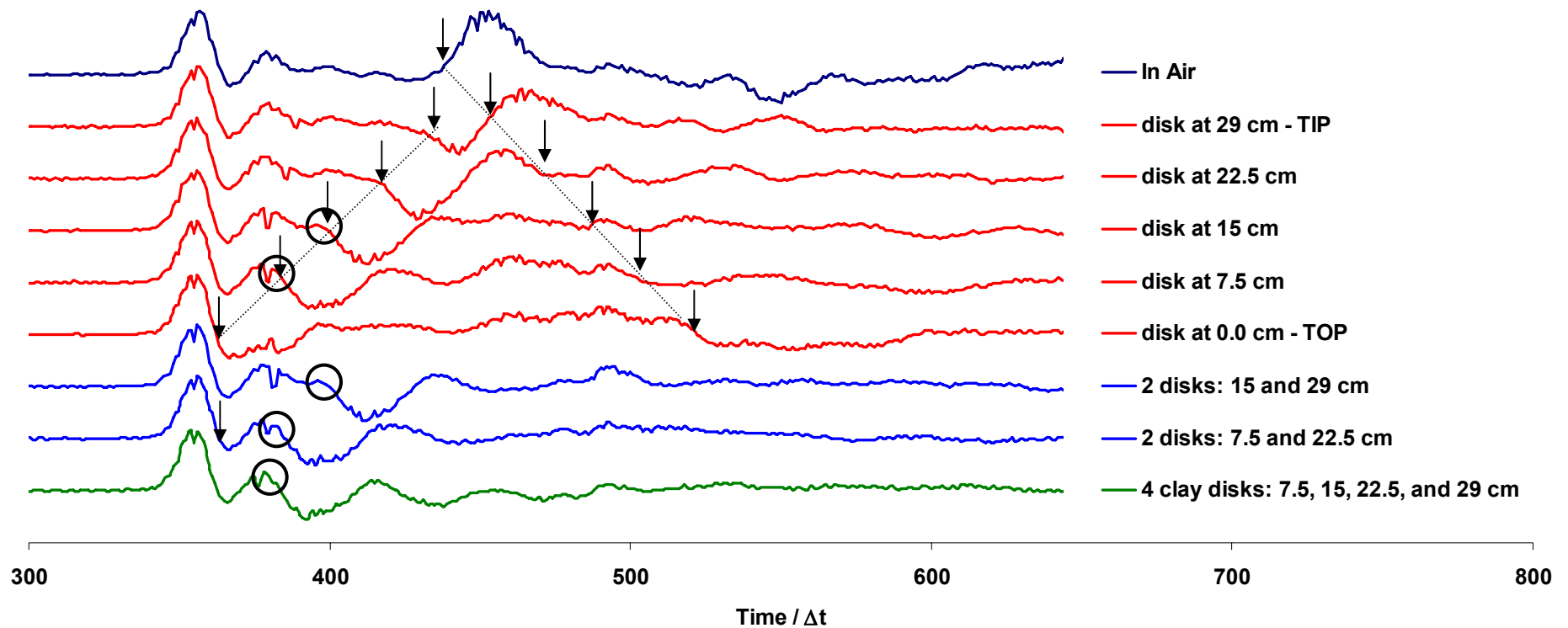
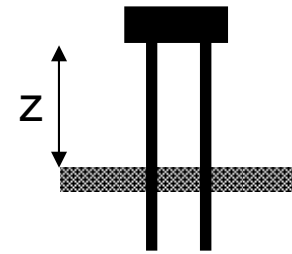


Photograph



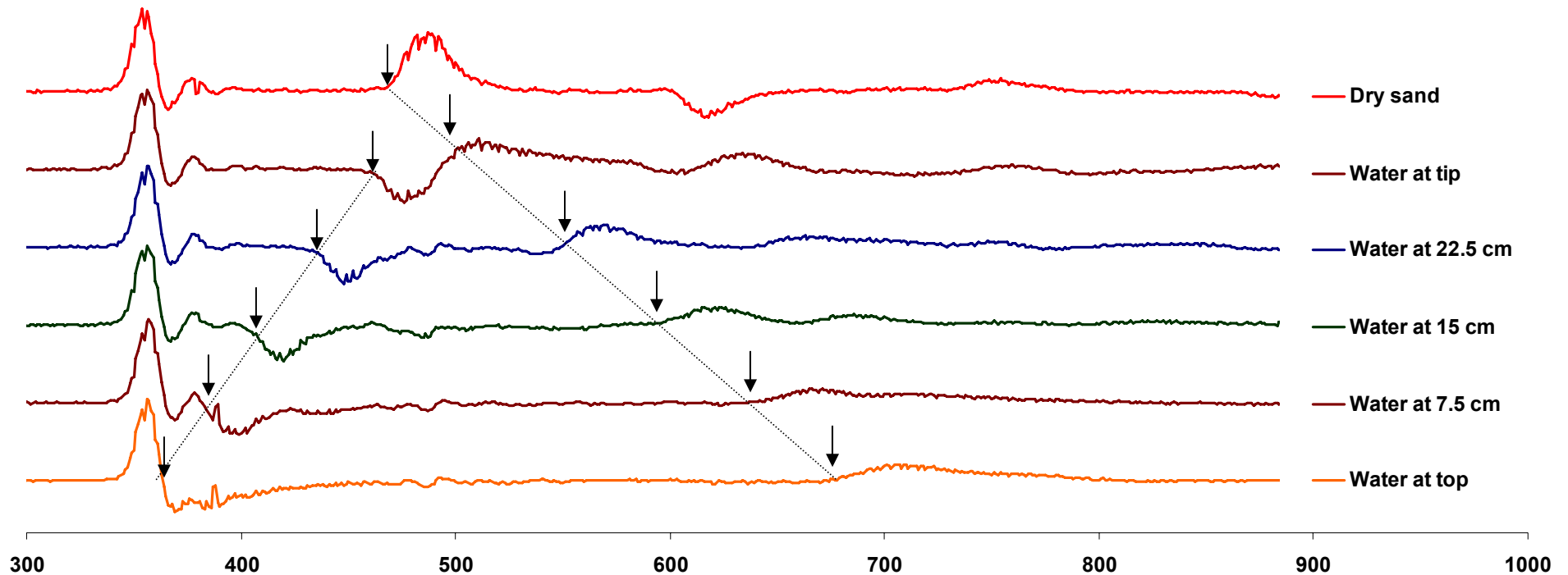
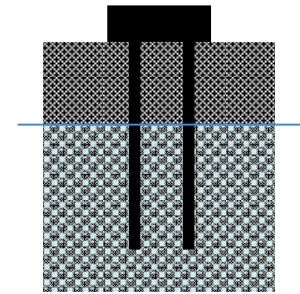
Needle probe measurements

Heterogeneity - Layering



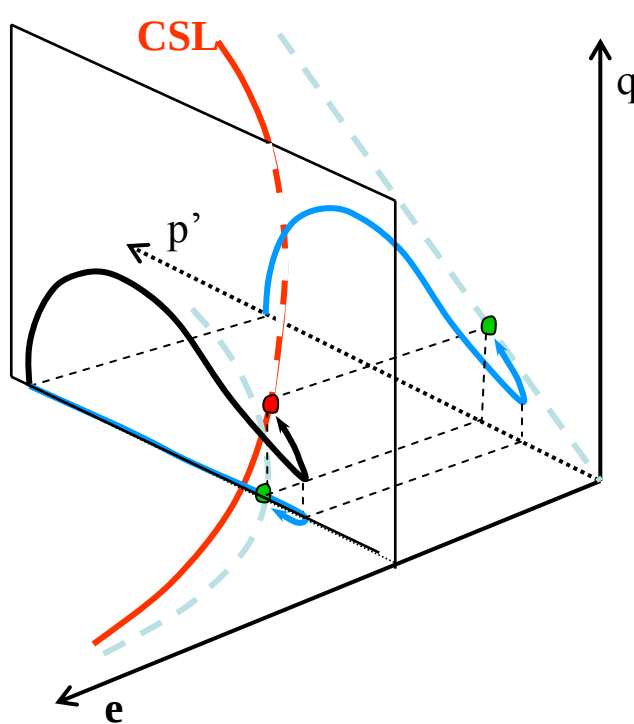
*a clay seam may hide the rest
(very high mismatch in this case)*

Heterogeneity in Water Content

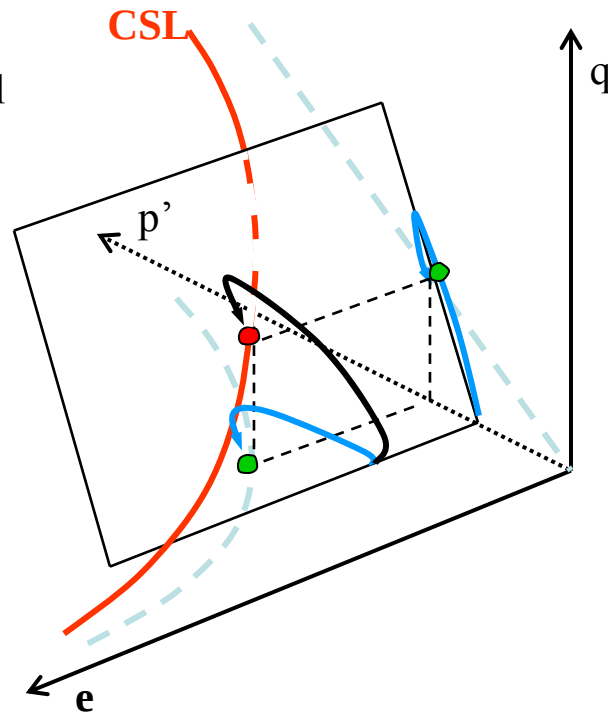


more than one primary reflections

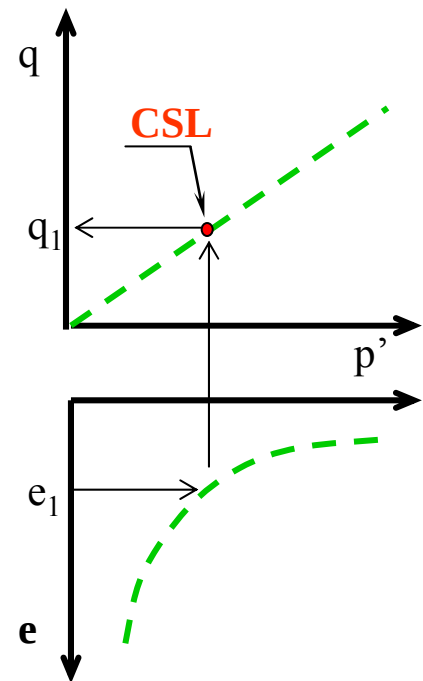
Insertion Effects



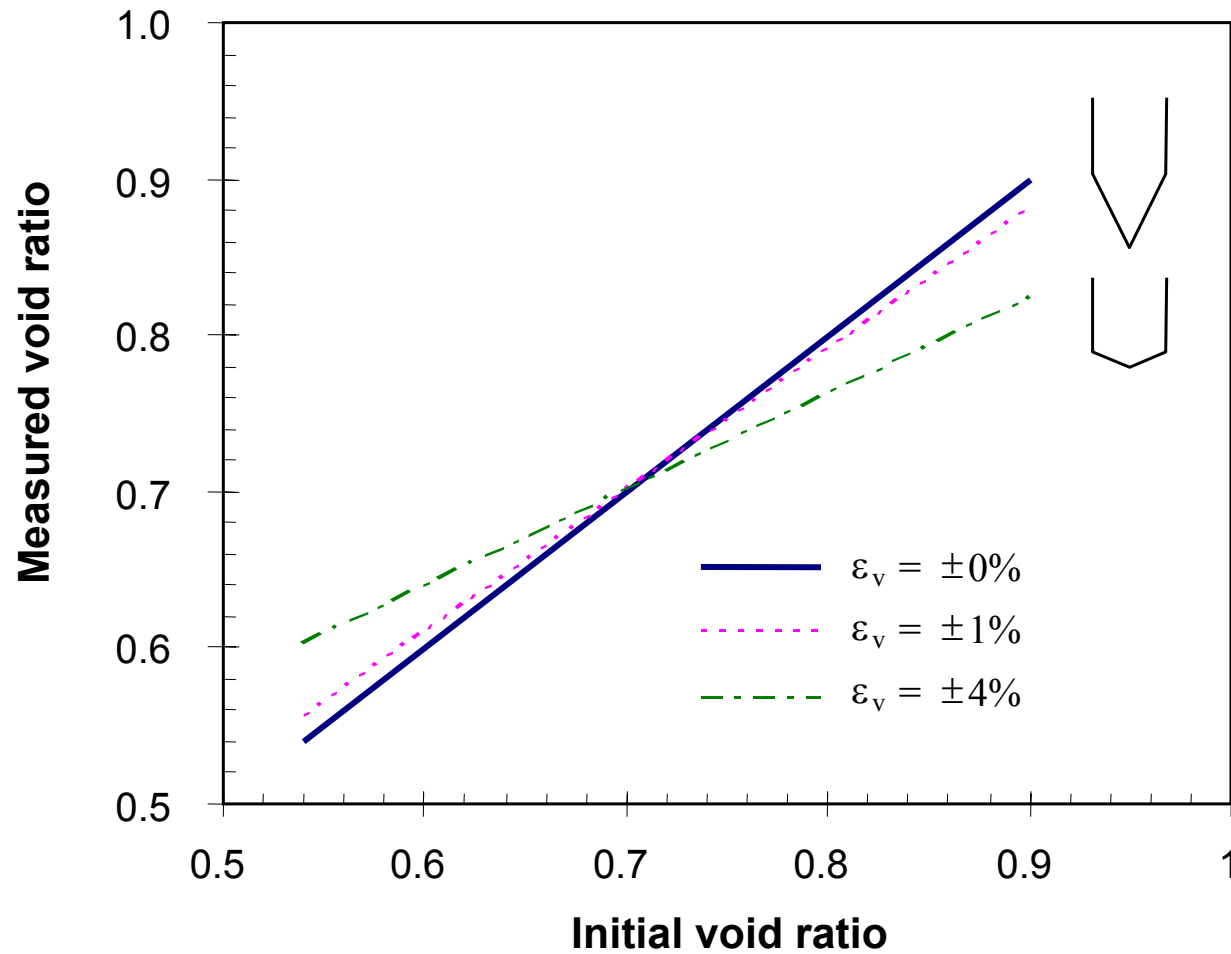
Undrained



Drained

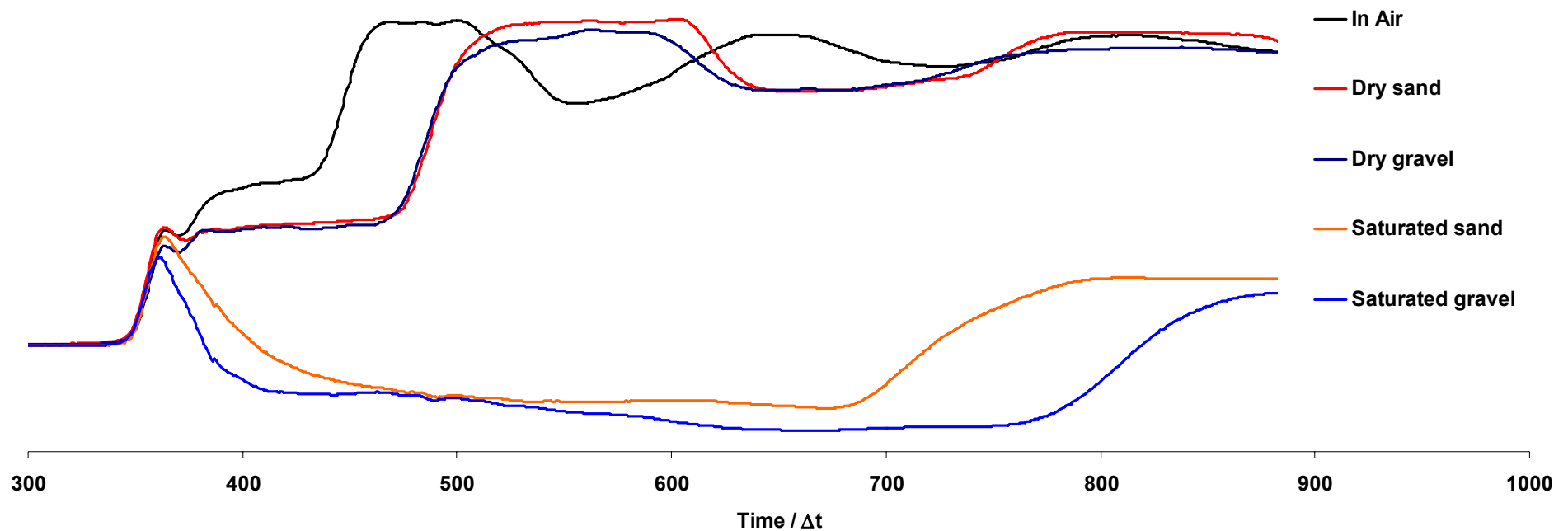


Insertion: Volumetric Strain = f(void ratio)



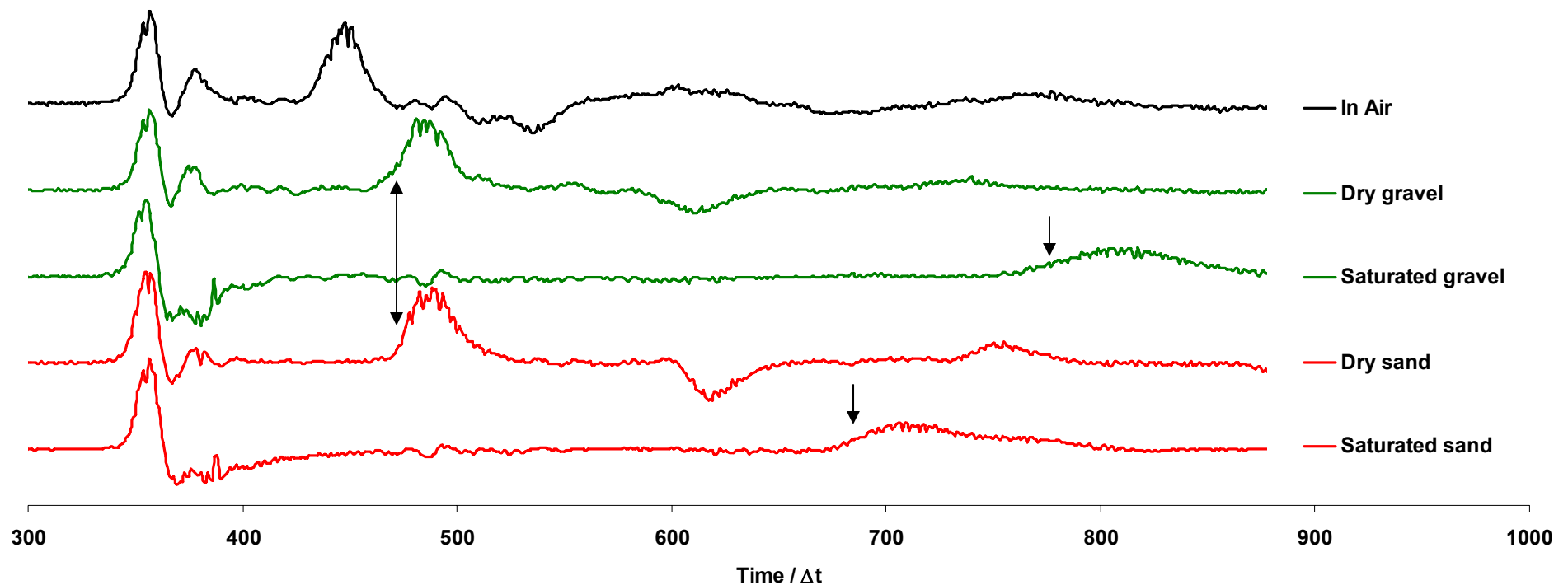
Large vs. Small Particles

Gravel – $d_{50} = 20 \text{ mm}$



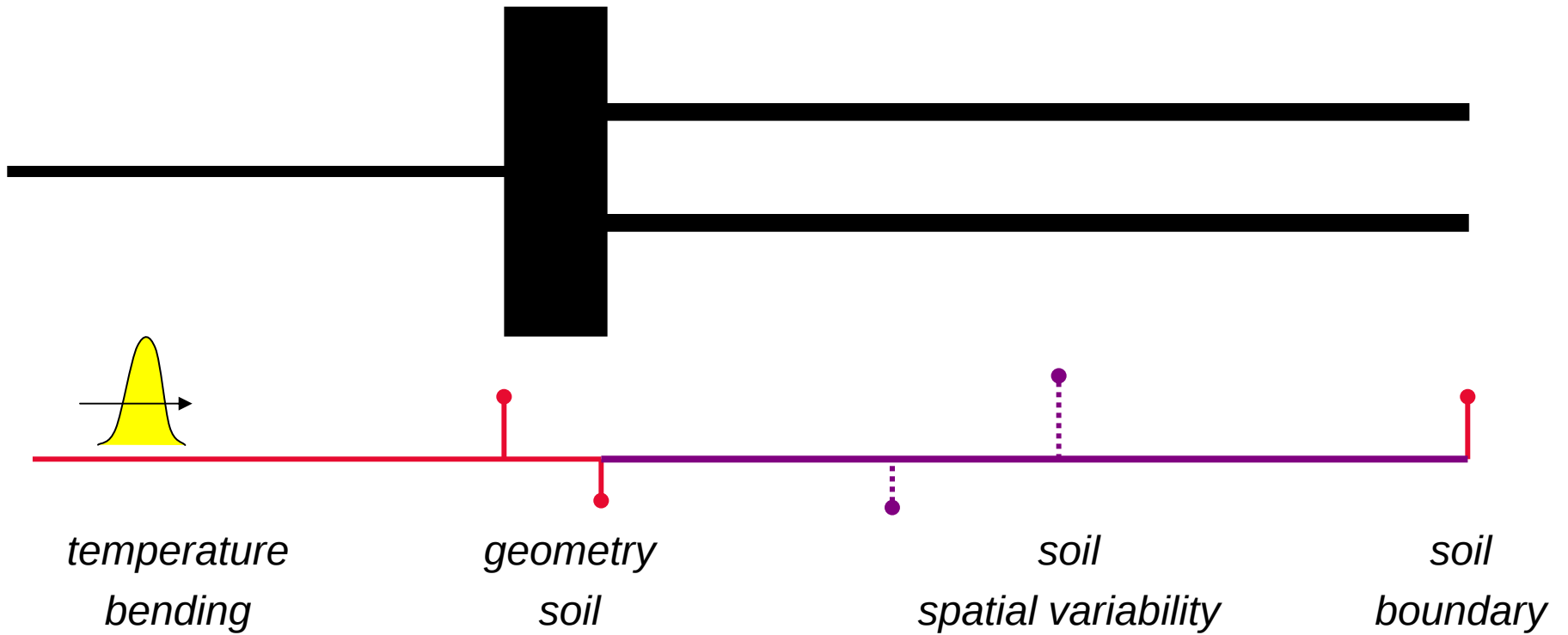
Large vs. Small Particles

Gravel – $d_{50} = 20 \text{ mm}$

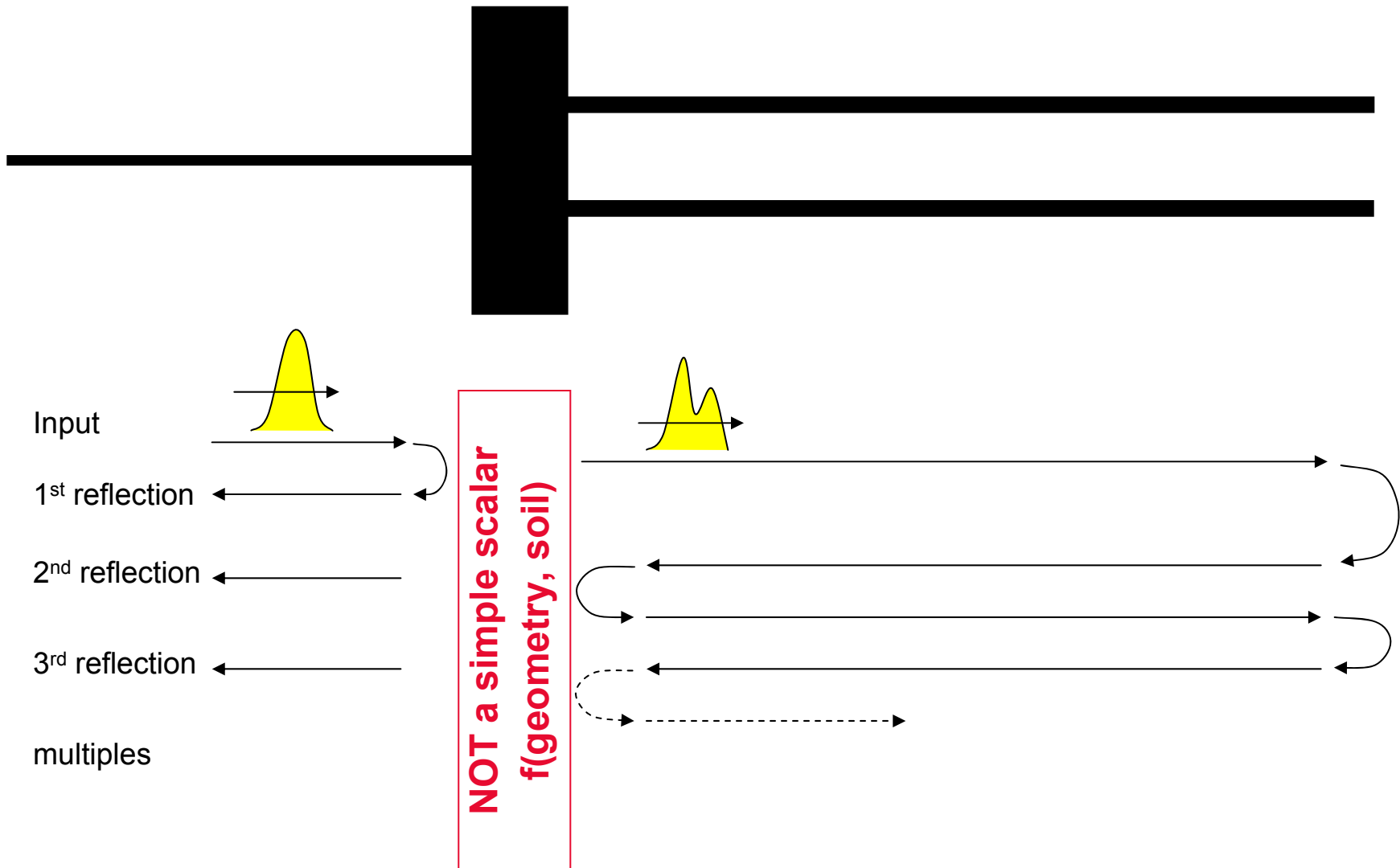


higher local porosity in gravel
Brillouin LP filter?

Summary



Summary



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

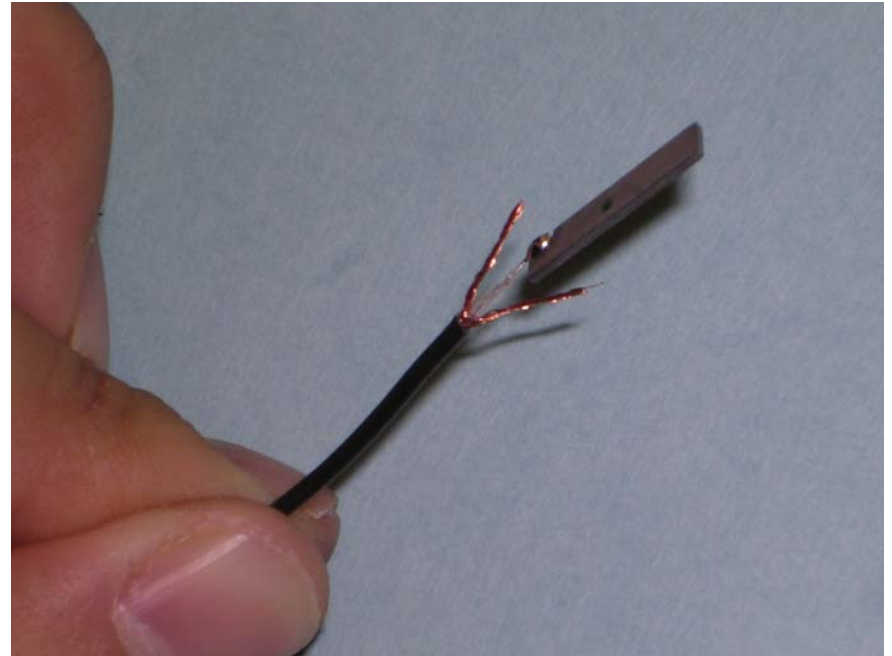
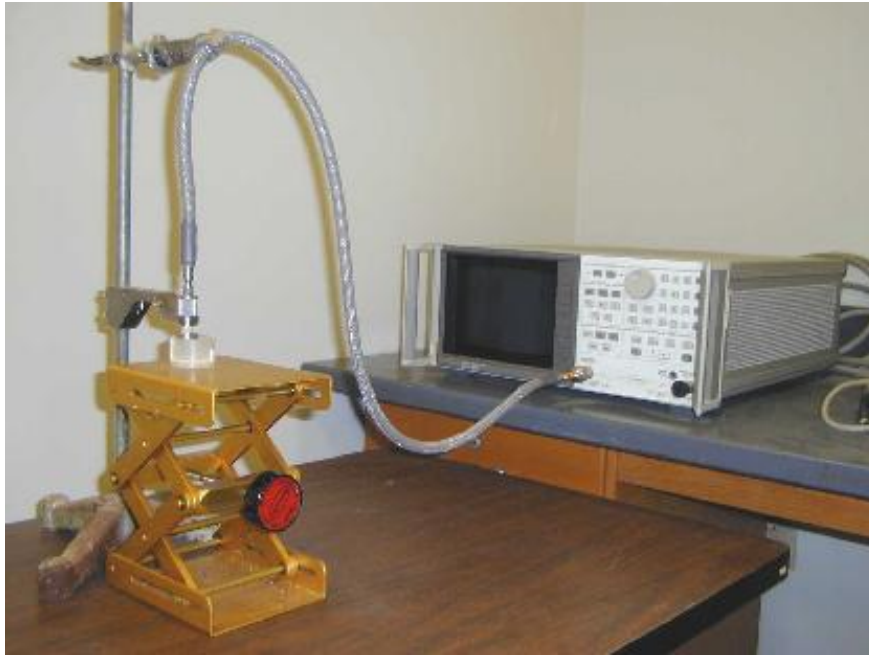
multiple interpretations of multiples

many unknowns → inversion may be ill defined

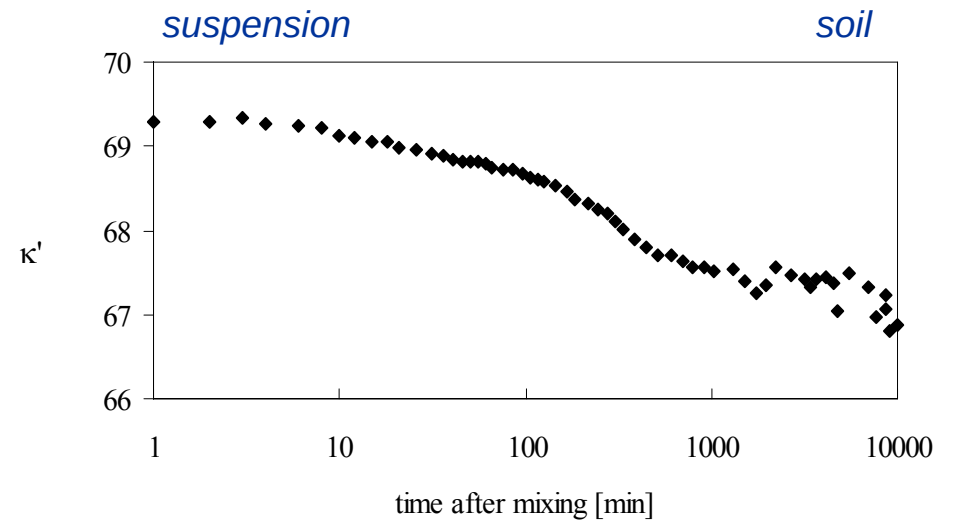
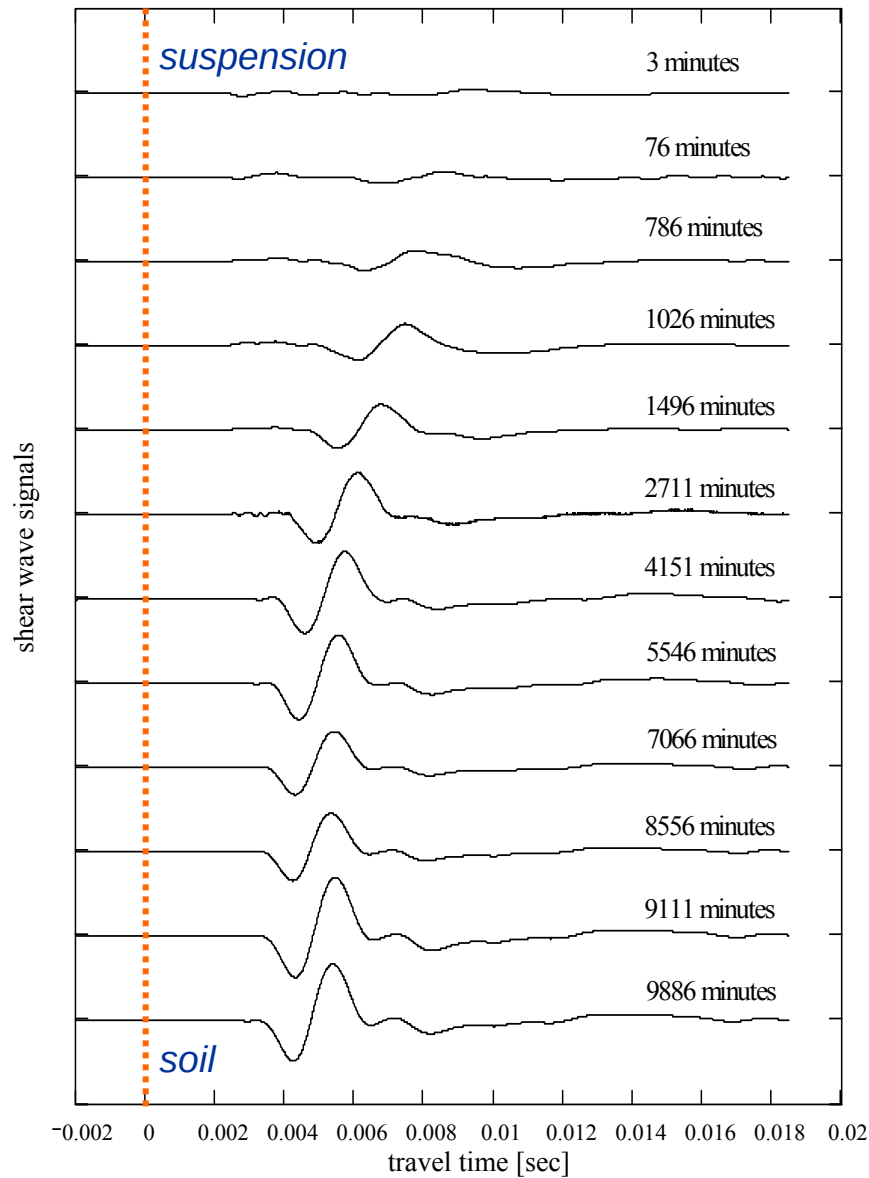
Information conservation → simple models (Ockham's criterion)

process monitoring

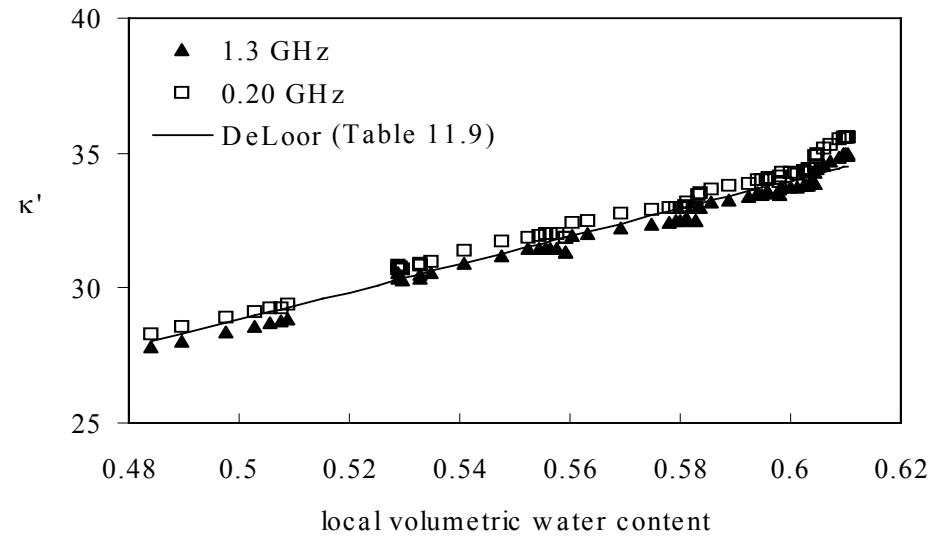
Measurements



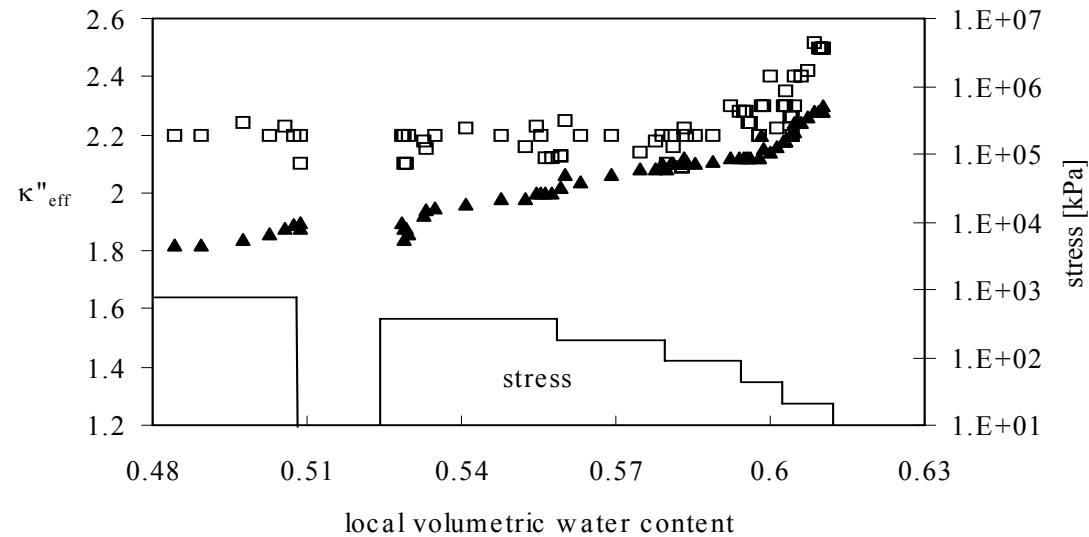
Sedimentation



Pressure diffusion

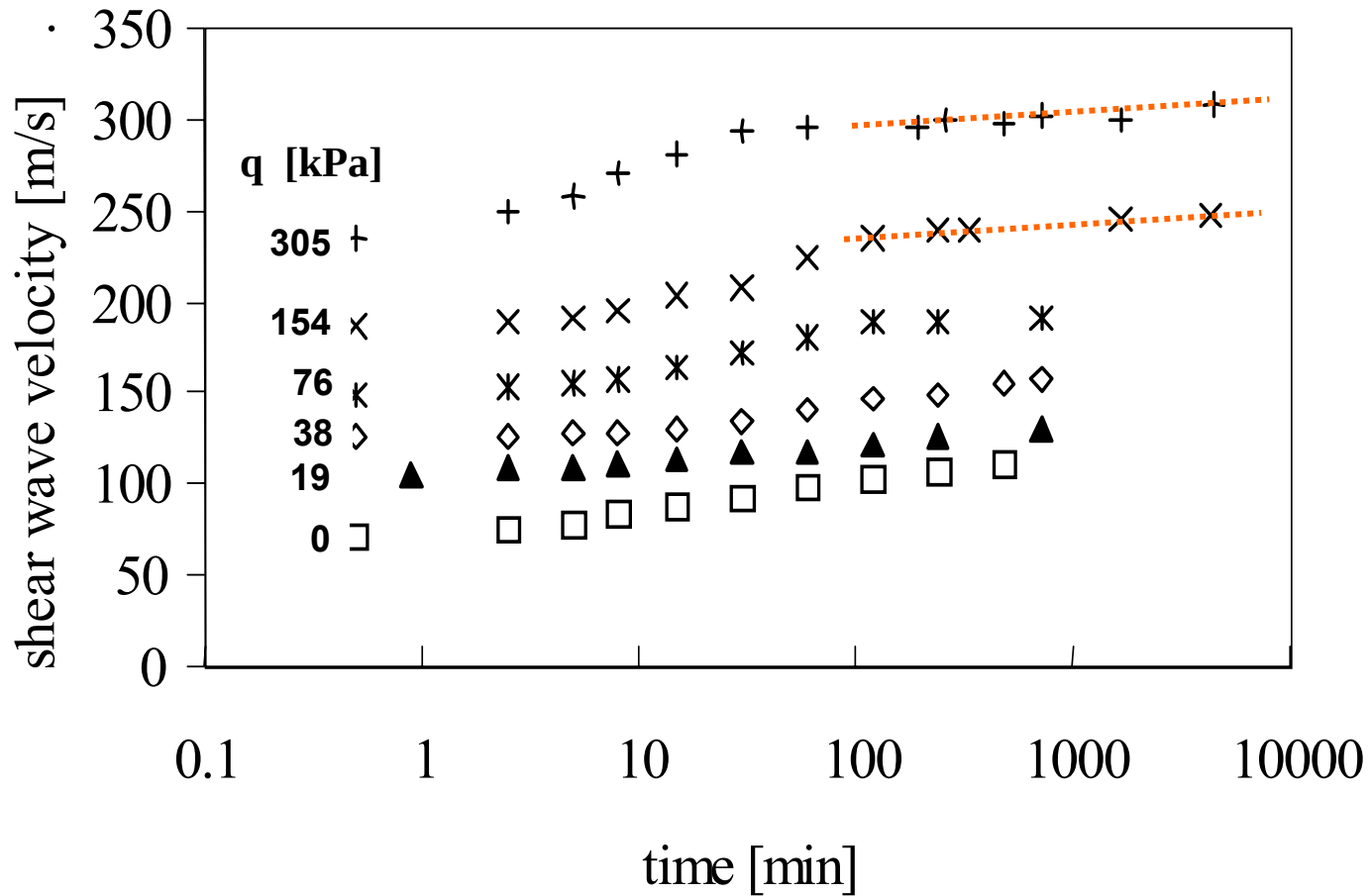


(a)



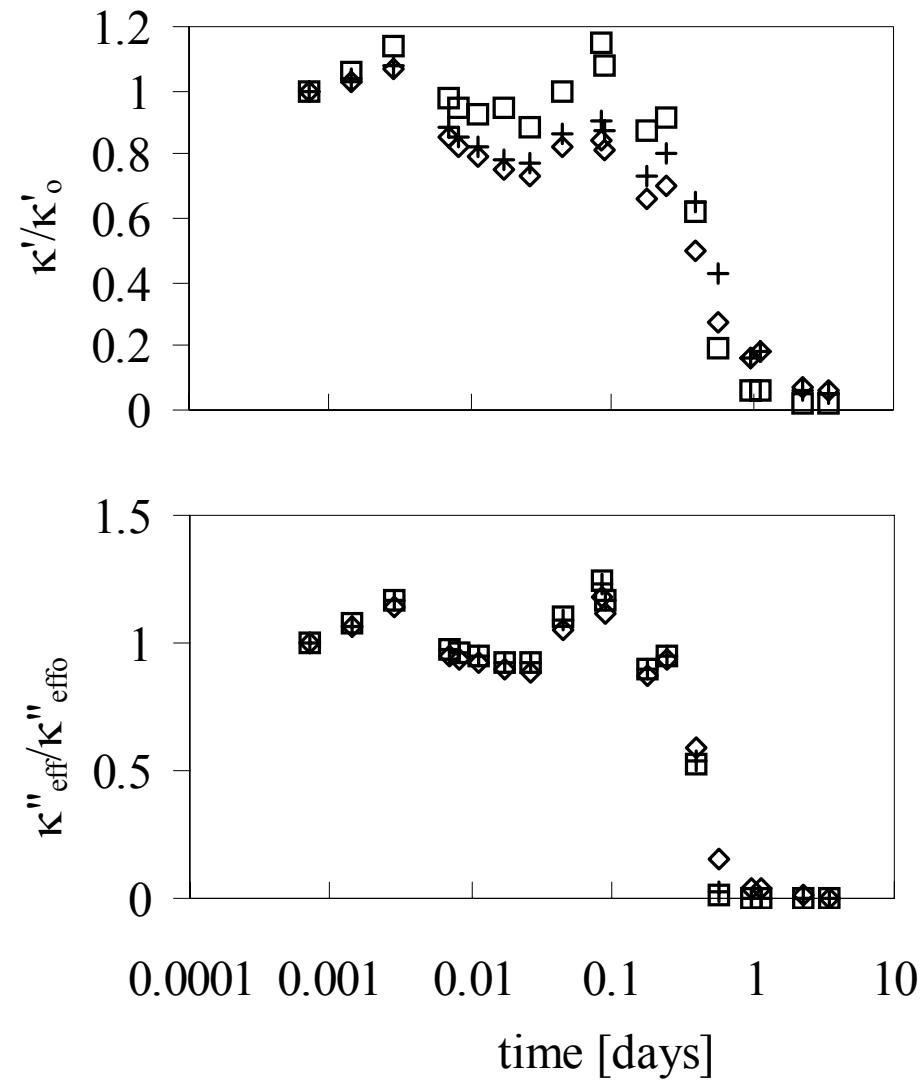
(b)

Pressure diffusion



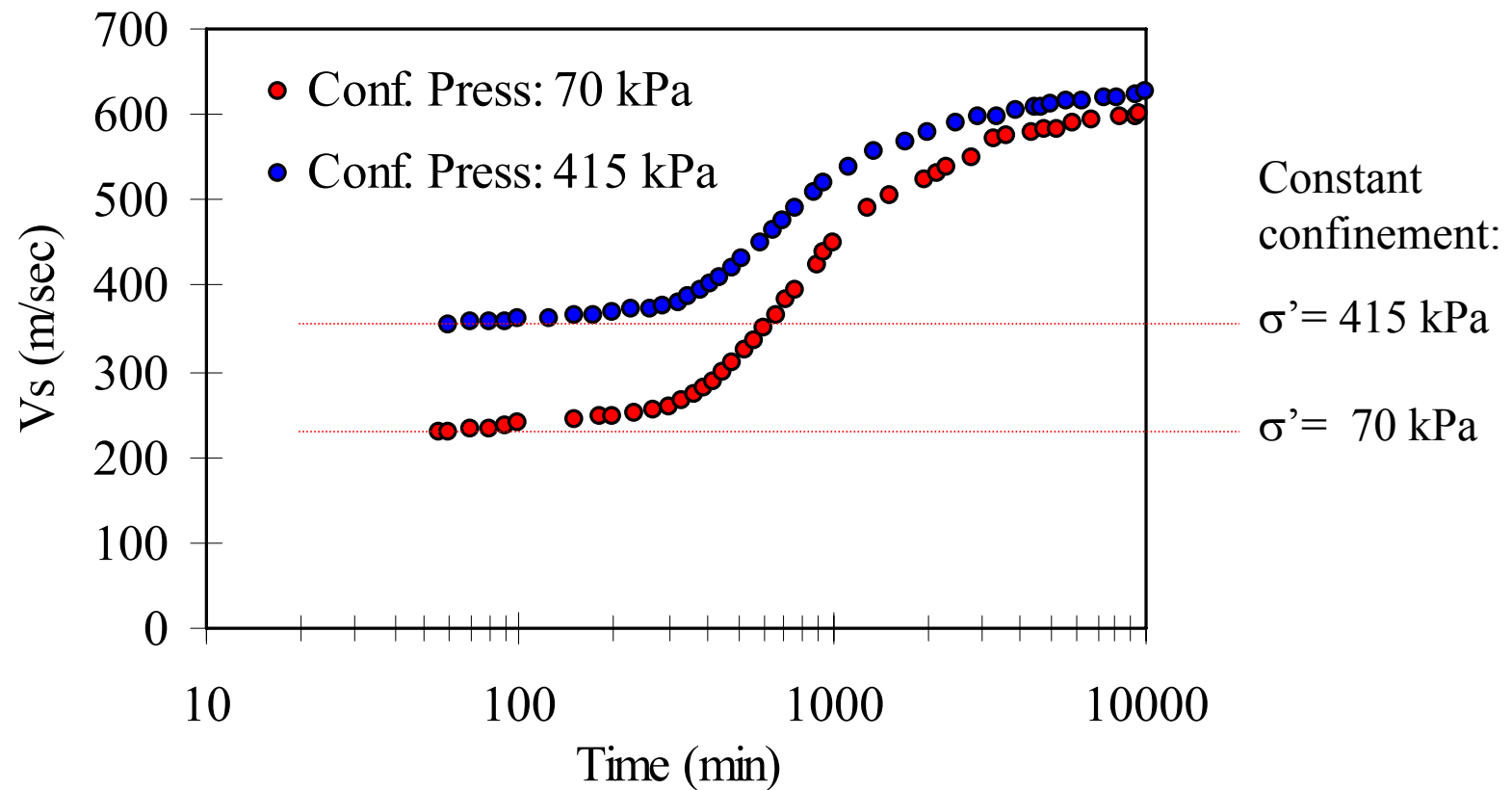
Cementation

(bentonite-cement)

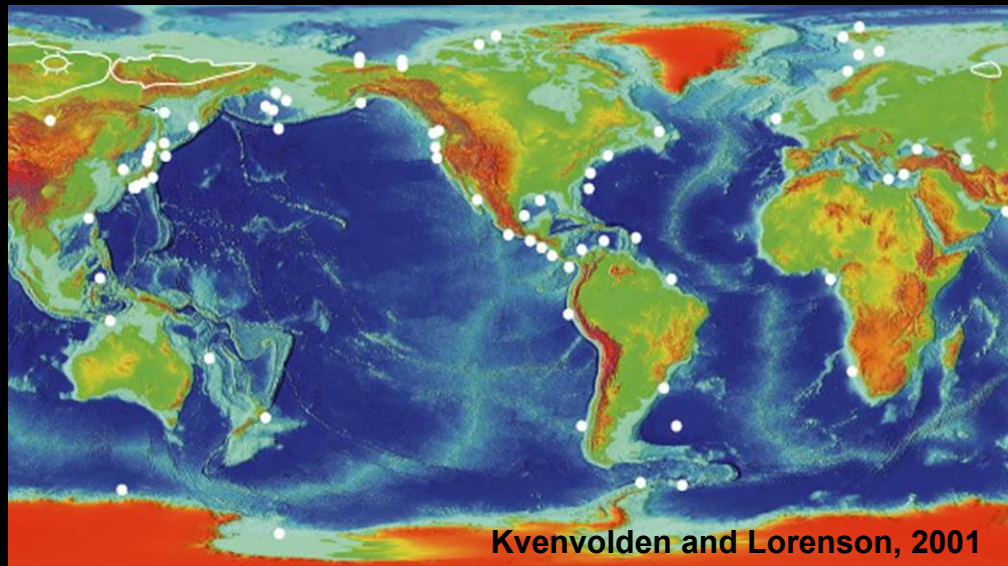


Cementation

(sand-cement)

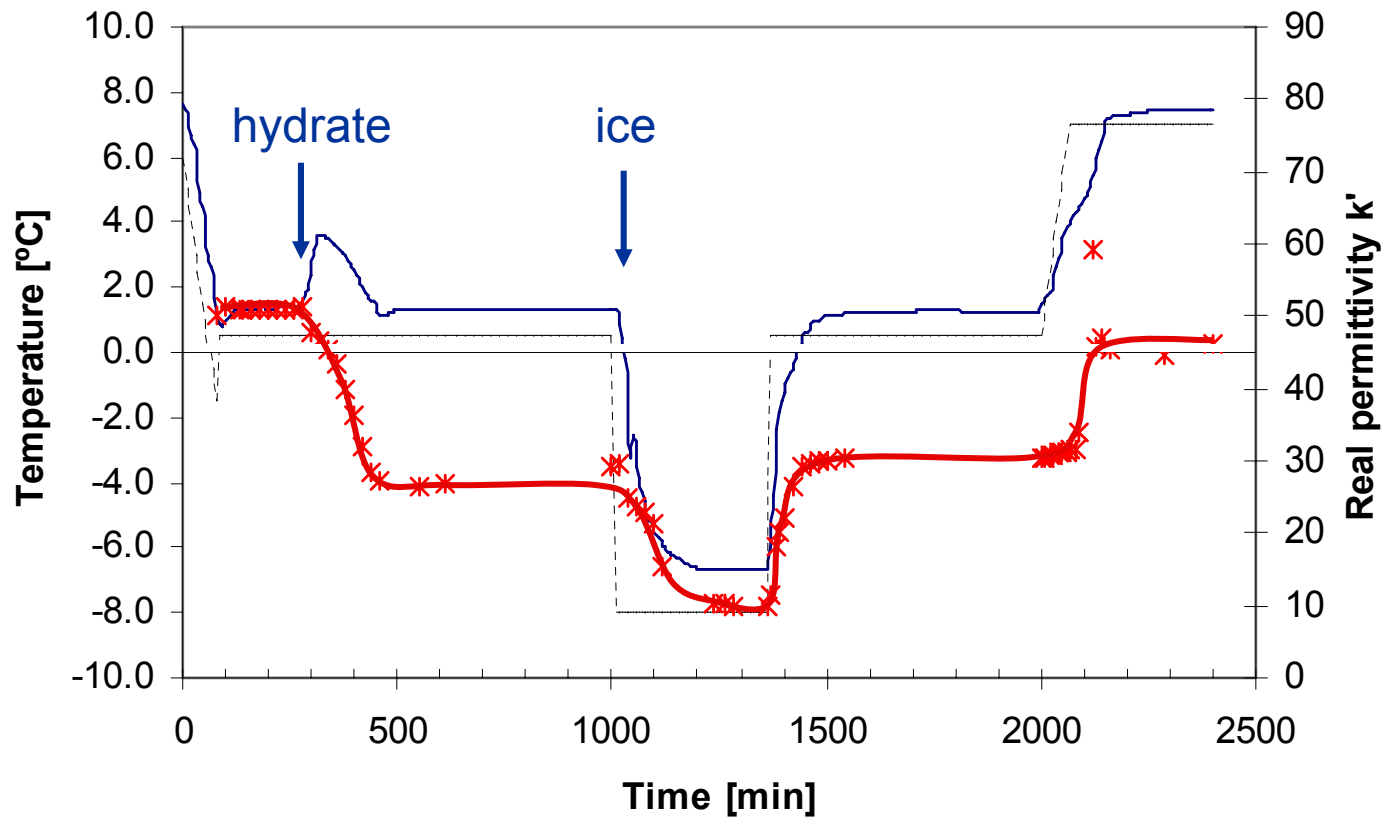


Gas hydrates



Real Permittivity

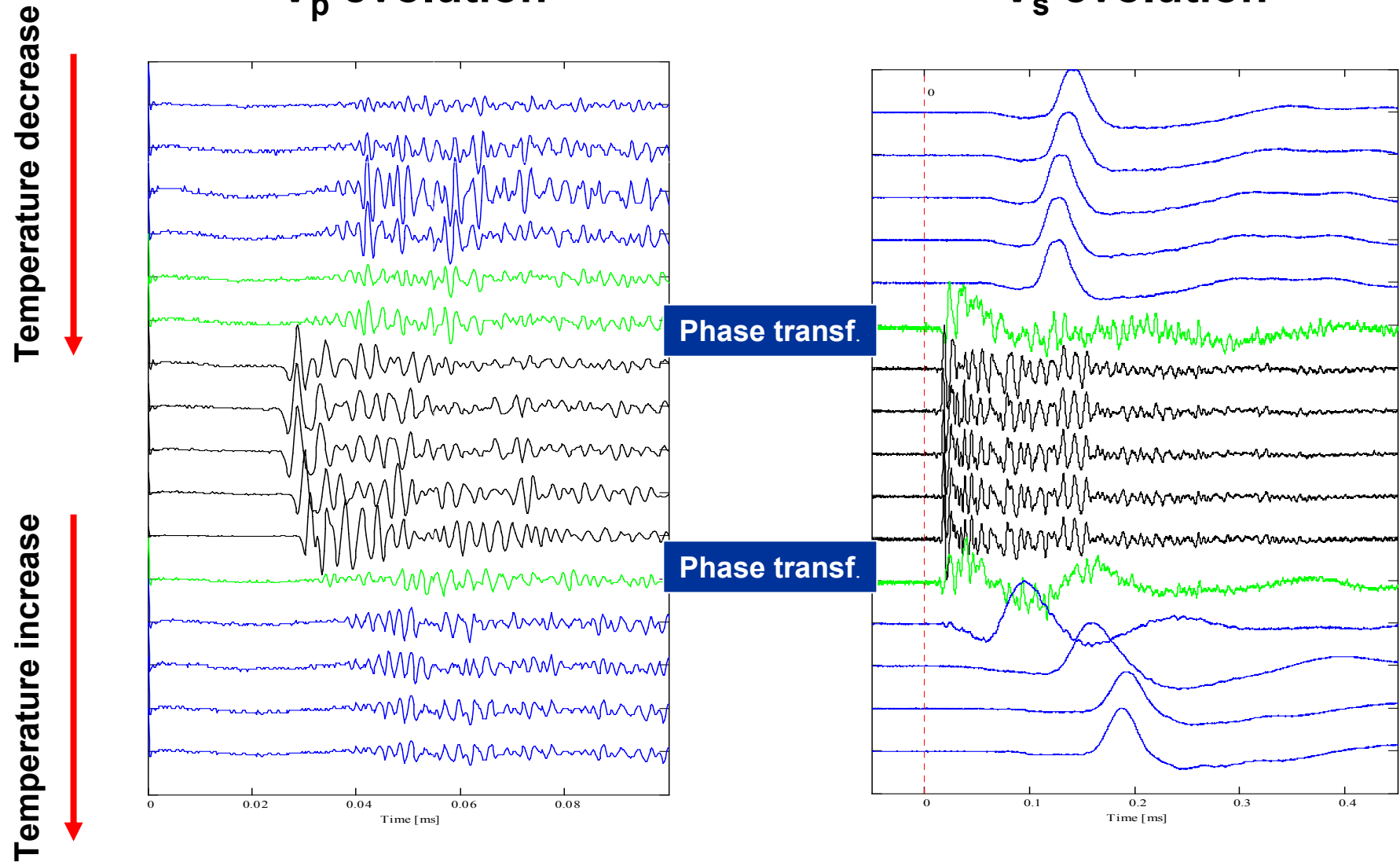
(Kaolinite + THF + H₂O)



Elastic waves

V_p evolution

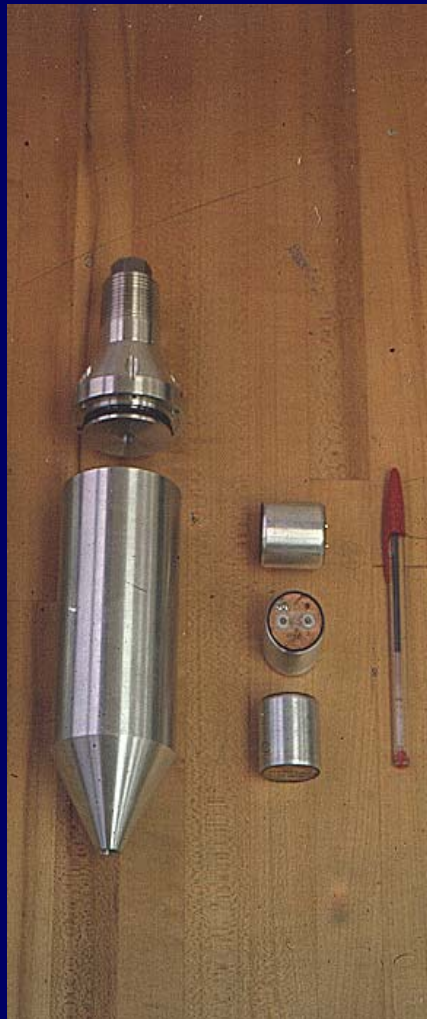
V_s evolution



Penetration-based Geophysical Systems



SV Source
(Fernandez)

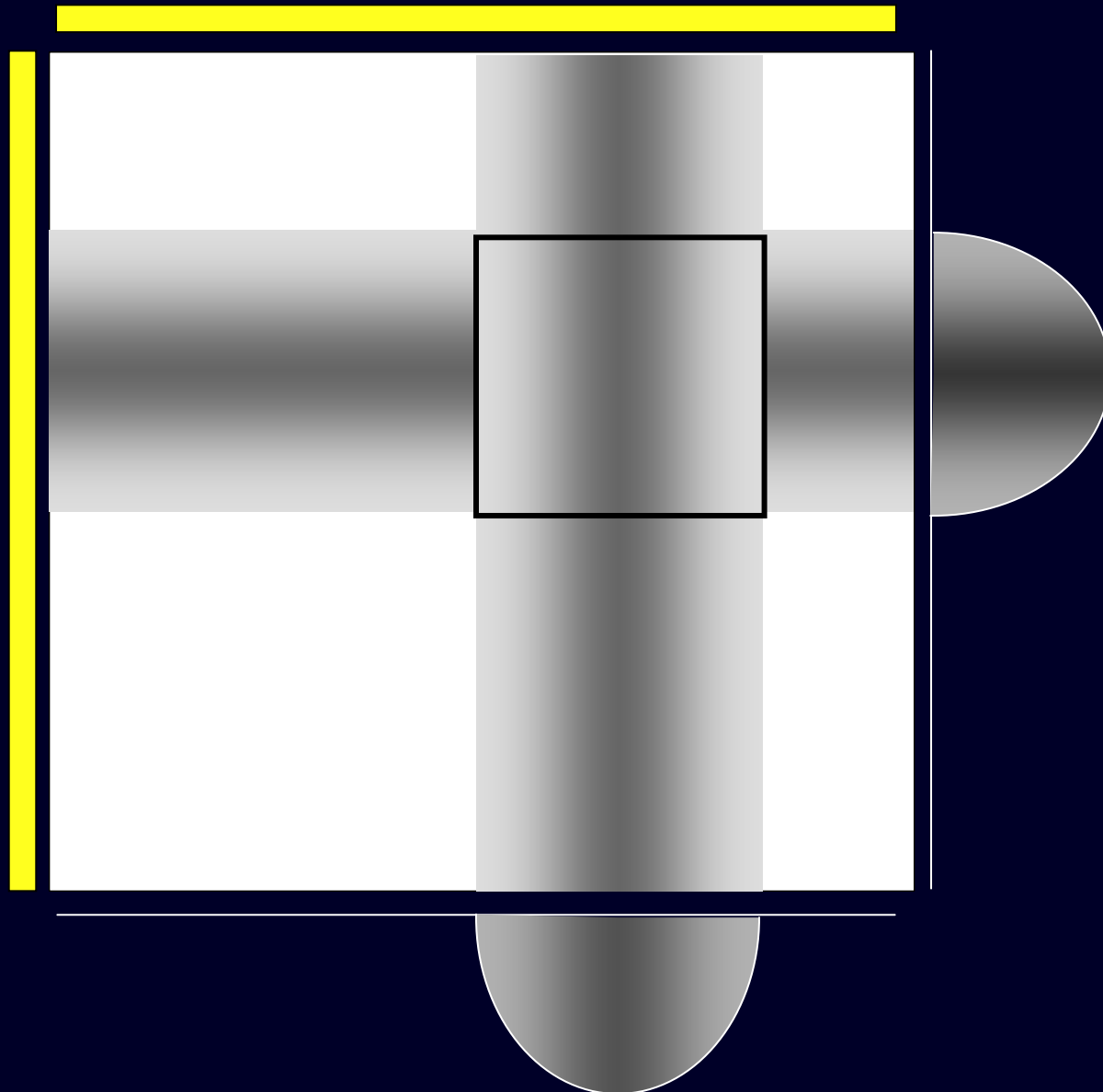


3D Geophone
(Stokoe – UT)



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

