

Aussois 2012

ELECTROMAGNETIC WAVES *and particulate materials*

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References:

Santamarina, J.C., in collaboration with Klein, K. and Fam, M. (2001). Soils and Waves, J. Wiley and Sons, Chichester, UK, 488 pages.

Klein, K. and Santamarina, J. C. (2003b). "Electrical Conductivity In Soils: Underlying Phenomena." *Journal of Environmental & Engineering Geophysics*, Vol. 8, No. 4, pp. 263-273.

Klein, K. and Santamarina, J. C. (1997). "Methods for Broad-Band Dielectric Permittivity Measurements (Soil-Water Mixtures, 5 Hz to 1.3 GHz)." *ASTM Geotechnical Testing Journal*, Vol. 20, No. 2, pp. 168-178.

Santamarina, J. C. and Fam, M. (1997b). "Dielectric Permittivity of Soils Mixed with Organic and Inorganic Fluids (0.02 GHz to 1.30 GHz)." *Journal of Environmental & Engineering Geophysics*, Vol. 2, No. 1, pp. 37-52.

Santamarina, J. C. and Fam, M. (1995). "Changes in Dielectric Permittivity and Shear Wave Velocity During Concentration Diffusion." *Canadian Geotechnical Journal*, Vol. 32, No. 4, pp. 647-659.

Some pdfs (these and related papers) available at <http://pmrl.ce.gatech.edu> under "Publications"

Soils: An Electrical View

Fluids - Water

Mass

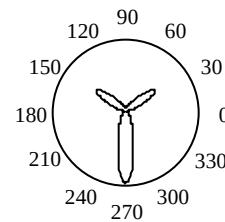
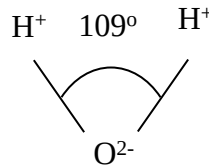
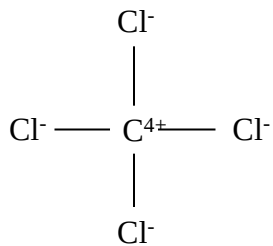
Bulk stiffness

Capillary forces

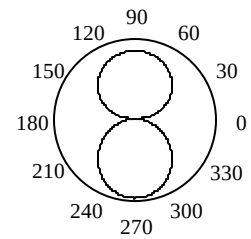
Seepage rate

Dipole

Hydration and double layers



$L=1.25r$

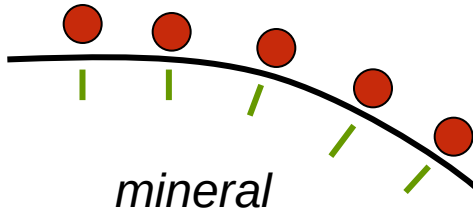
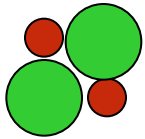


$L=10r$

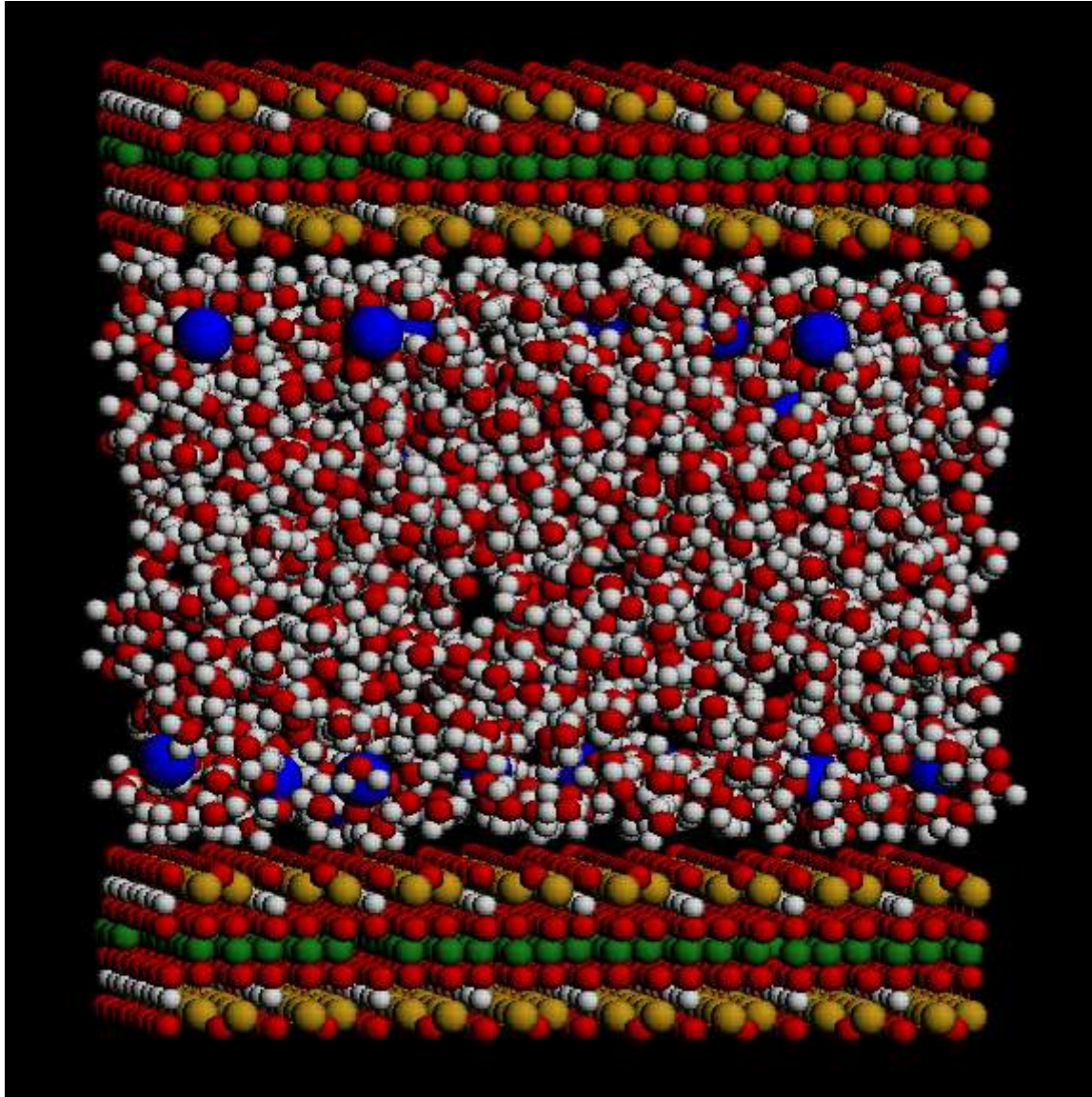
Electrical View of Soils

dry soil

Precipitated salt



Wet clay



Laponite
1200 H₂O
24 Na⁺

N. Skipper (UCL)

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

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

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

Electromagnetic Parameters

	<i>Free space</i>	<i>Materials</i>
Conductivity	0	σ
Permittivity	ϵ_0	$\epsilon^* = \epsilon' - j \epsilon''$
Permeability	μ_0	$\mu = \mu' - j \mu''$

Wave Equation

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

in real materials

Consider solution of the form (fluctuates in y - propagates in x)

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

Then

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

if

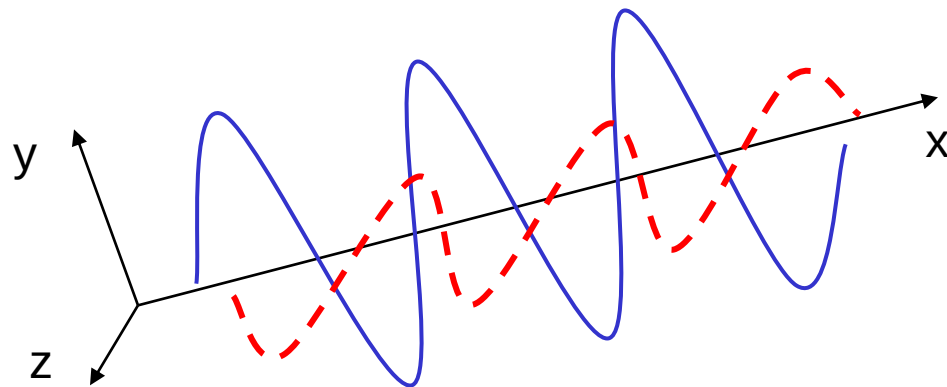
$$\mathbf{E}_y = E_o e^{-\alpha x} e^{j\omega t - \kappa x}$$

Faraday

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

then

$$H_z = -j \frac{\gamma^*}{\mu \omega} E_o e^{j\omega t - \gamma^* x} = -j \frac{\gamma^*}{\mu \omega} E_y$$



Phase Velocity

$$V_{\text{ph}} = \frac{\omega}{\kappa} = \frac{\omega}{\text{Im}(\alpha + j\kappa)} = \frac{\omega}{\text{Im} \sqrt{j\omega\sigma\mu^* - \omega^2\varepsilon^*\mu^*}}$$

In free space

$$\mu^* = \mu_0 \quad \varepsilon^* = \varepsilon_0 \quad \sigma = 0$$

$$V_{\text{ph}} = c_0 = \frac{1}{\sqrt{\varepsilon_0\mu_0}} = 3 \cdot 10^8 \text{ m/s}$$

In non-ferromagnetic dielectric

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

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

Attenuation

$$\alpha = \operatorname{Re} \sqrt{j\omega\sigma\mu^* - \omega^2\epsilon^*\mu^*}$$

In free space

$$\mu^* = \mu_0 \quad \epsilon^* = \epsilon_0 \quad \sigma = 0$$

$$\alpha = 0$$

In non-ferromagnetic material

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

$$\alpha = \frac{\omega \sqrt{\frac{\epsilon'}{\epsilon_0}}}{c_0} \sqrt{\frac{1}{2} \sqrt{1 + \tan^2 \delta} - 1}$$

Electromagnetic Spectrum

	Frequency [Hz]	Wave	Wave length [m]
	10^{22}		10^{-14}
	10^{21}	Gamma rays	10^{-13}
	10^{20}		10^{-12}
	10^{19}		10^{-11}
	10^{18}	X rays	10^{-10}
	10^{17}		10^{-9}
	10^{16}	Ultraviolet	10^{-8}
	10^{15}		10^{-7}
	10^{14}	Visible *	10^{-6}
	10^{13}	Infrared	10^{-5}
	10^{12}		10^{-4}
	10^{11}	Microwaves	10^{-3}
	10^{10}		10^{-2}
GHz	10^9		10^{-1}
	10^8		1
	10^7		10^1
MHz	10^6	Radio waves	10^2
	10^5		10^3
	10^4		10^4
KHz	10^3		10^5
	10^2		10^6
	10^1		10^7



and God said:

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

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

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

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

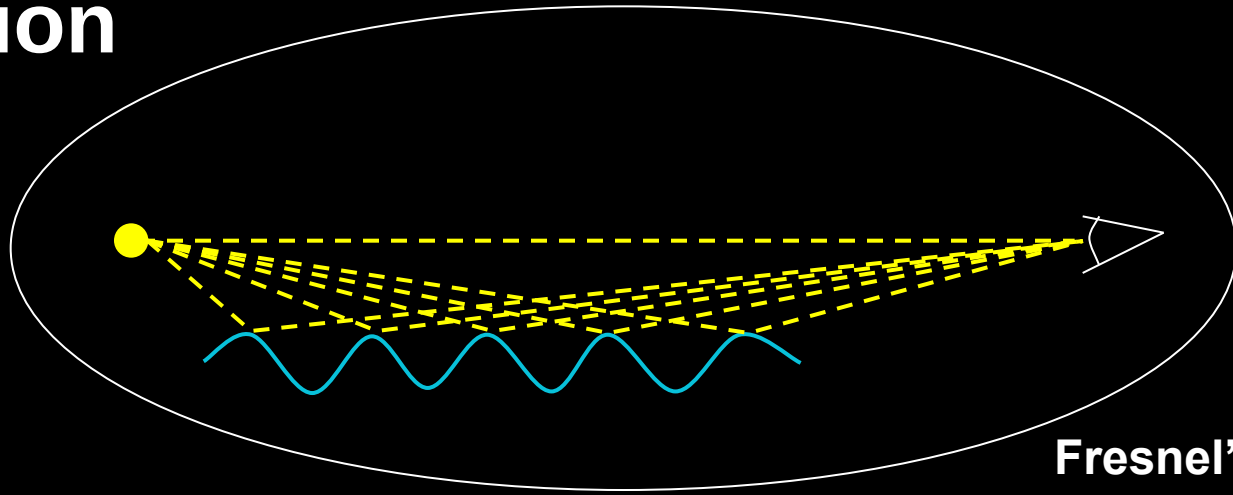
and there was light...!





Light-surface interaction
(Atlanta Airport)
and blue butterflies?

Reflection



van Gogh - La Nuit Etoilee

Scatter



Electromagnetic Material Properties

Electromagnetic Parameters

Conductivity

$$\sigma$$

Permittivity

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

Permeability

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

Note: Losses

Ohmic conduction losses σ

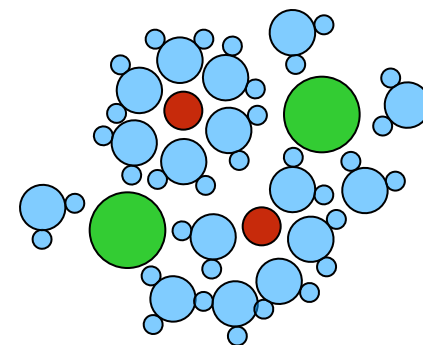
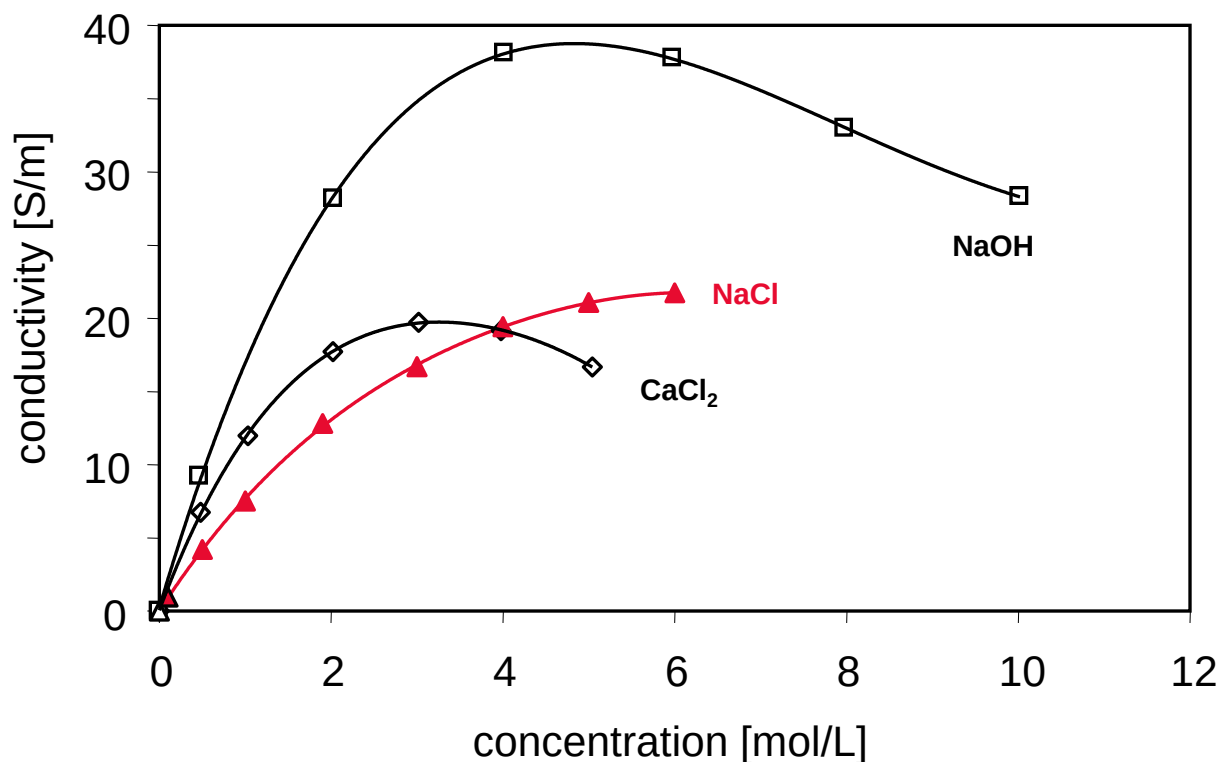
Polarization losses $\epsilon''\omega$

Magnetization losses $\mu''\omega$

Non-Ferromagnetic $\tan\delta = \frac{\epsilon'' + \sigma\omega}{\epsilon'}$

Conductivity $\Rightarrow$ charges & mobility

Electrical Conductivity of the Pore Fluid



At low concentration (P. Annan):

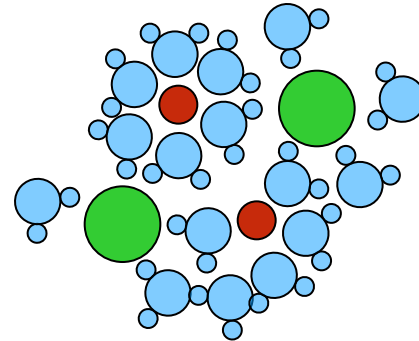
$$\sigma_{\text{fl}} [\text{mS} / \text{m}] = 0.15 \cdot \text{TDS} [\text{mg} / \text{L}]$$

Archie's Law?

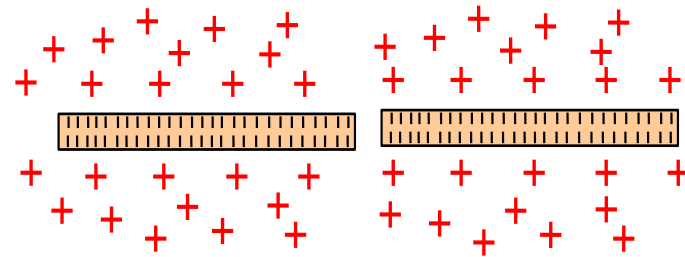
$$\sigma_{\text{soil}} = \alpha n^{\beta} \sigma_{\text{el}}$$

Electrical Conductivity

Pore fluid



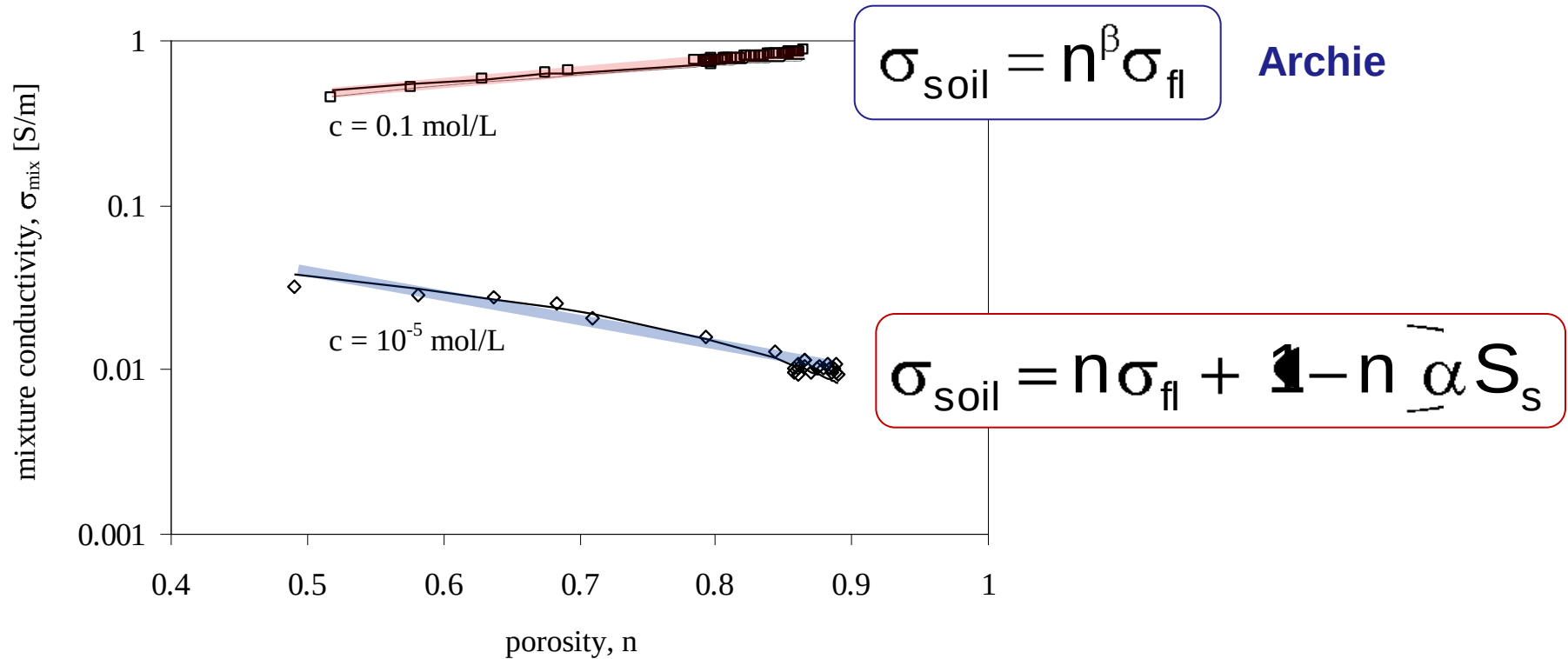
Surface conduction



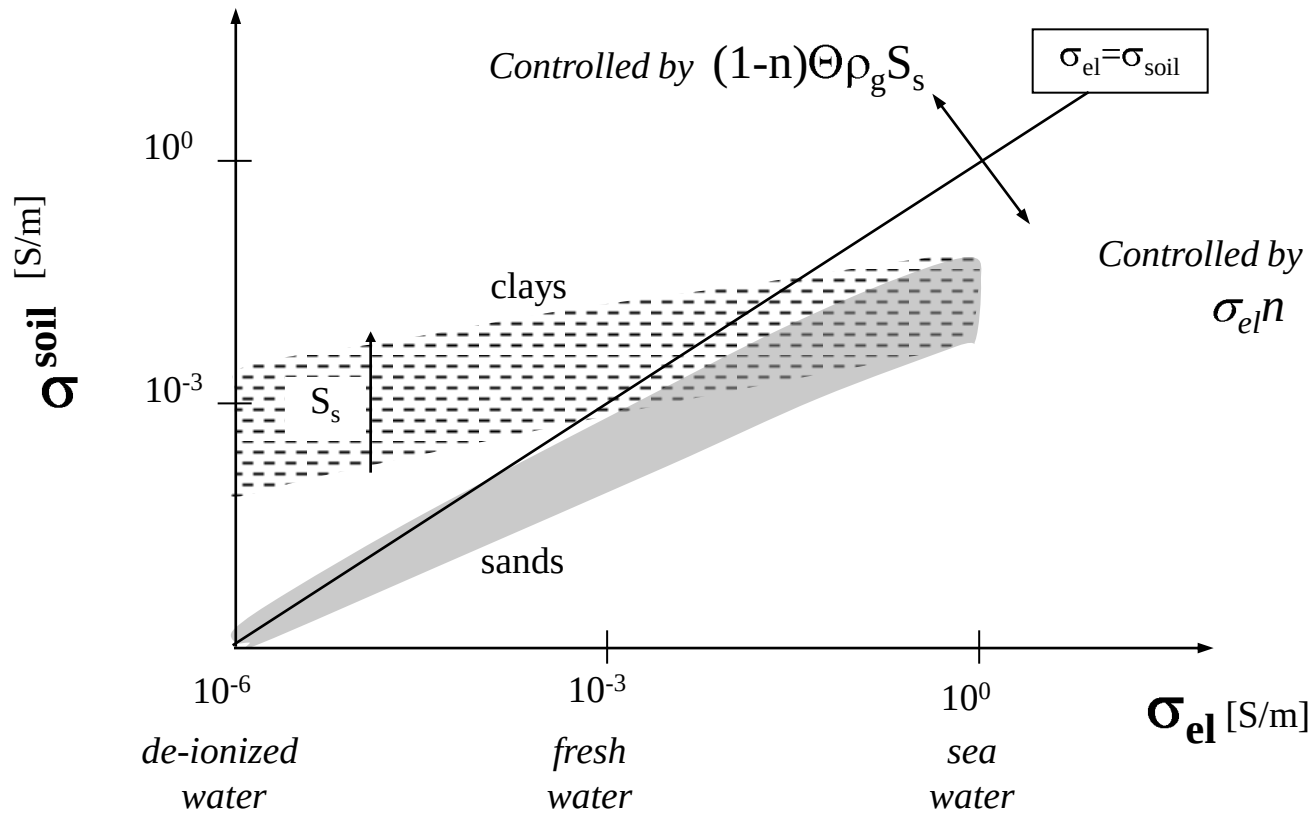
Wet Soil

$$\sigma_{\text{soil}} = n\sigma_{\text{el}} + (1-n)\bar{\Theta}\rho_g S_s$$

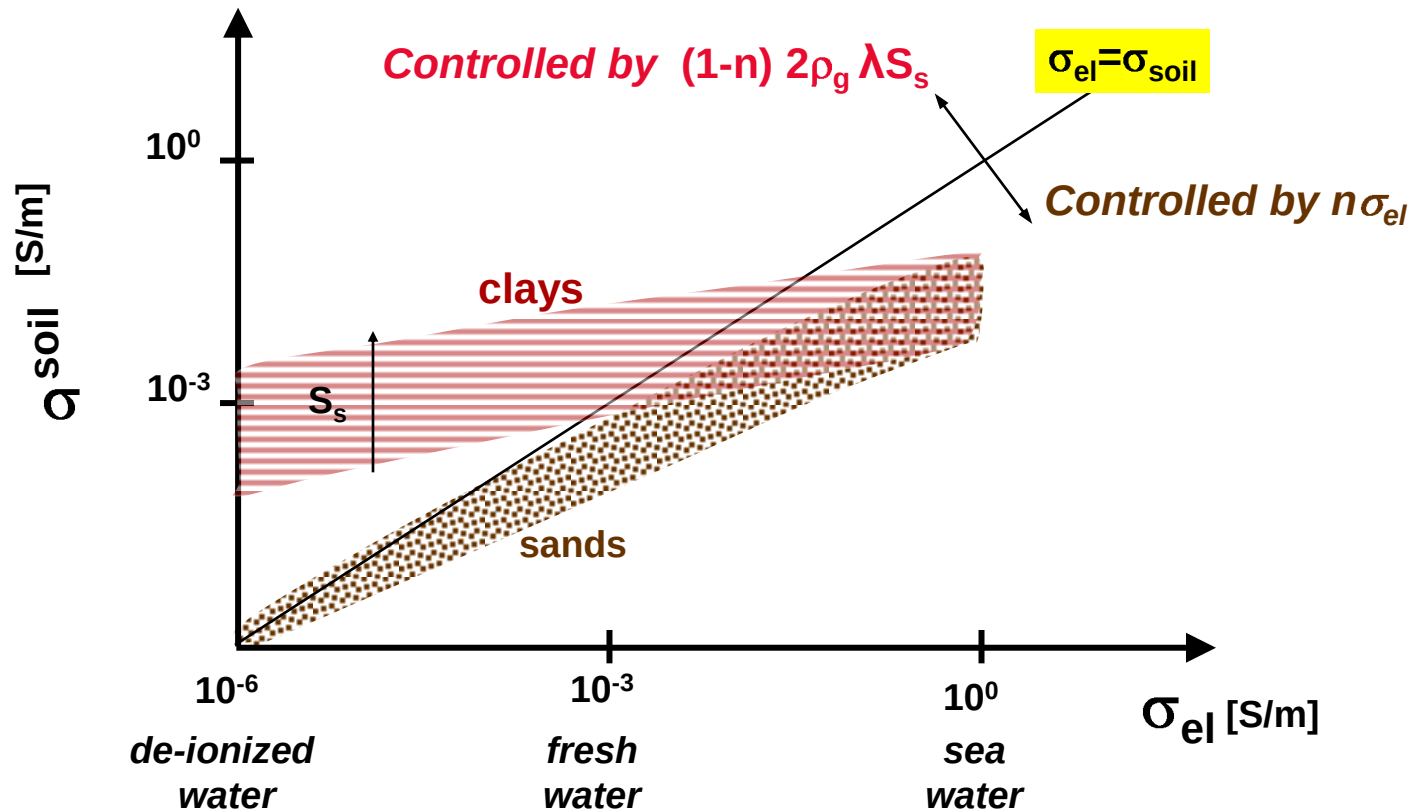
Electrical Conductivity of Soils



Summary

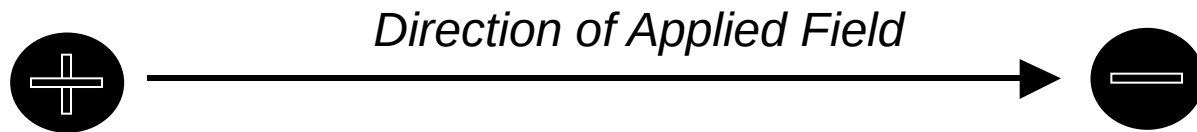


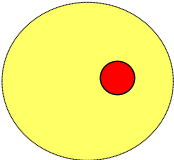
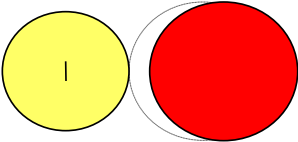
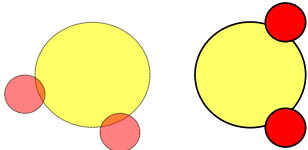
Summary: Electrical Conductivity



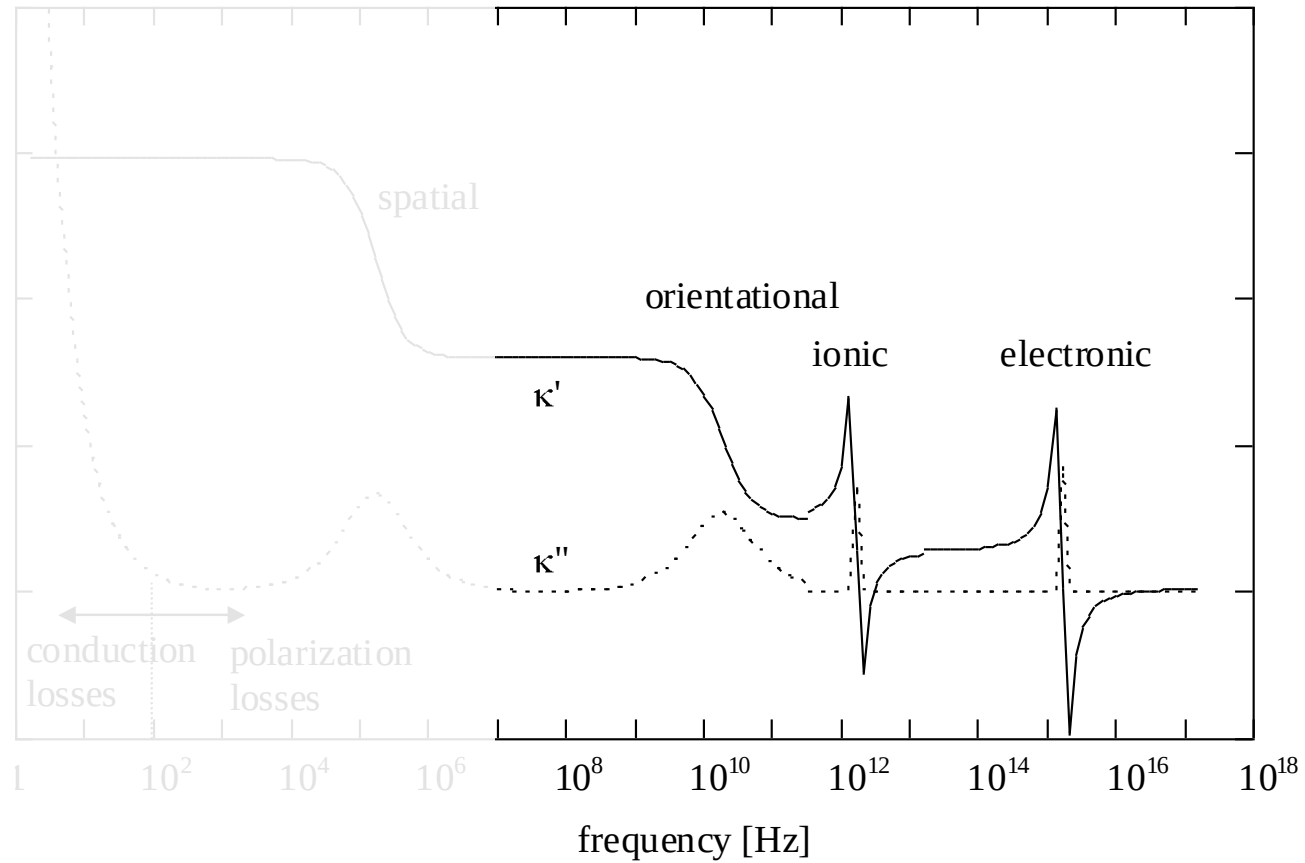
Permittivity → Polarizability

Single phase

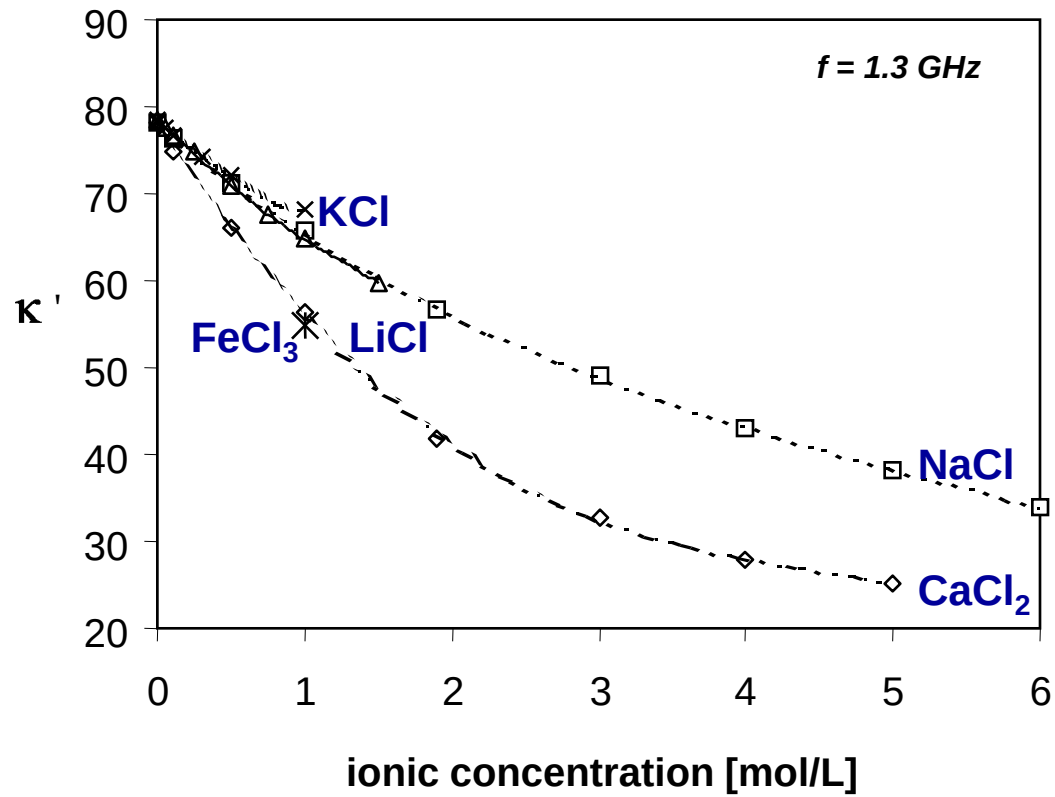


Electronic (resonance)	Ionic (resonance)	Orientational (relaxation)
		
$t = 10^{-16} \text{ s}$ (Ultraviolet)	$t = 10^{-13} \text{ s}$ (Infrared)	$t = 9 \times 10^{-12} \text{ s}$ (Microwave- water)

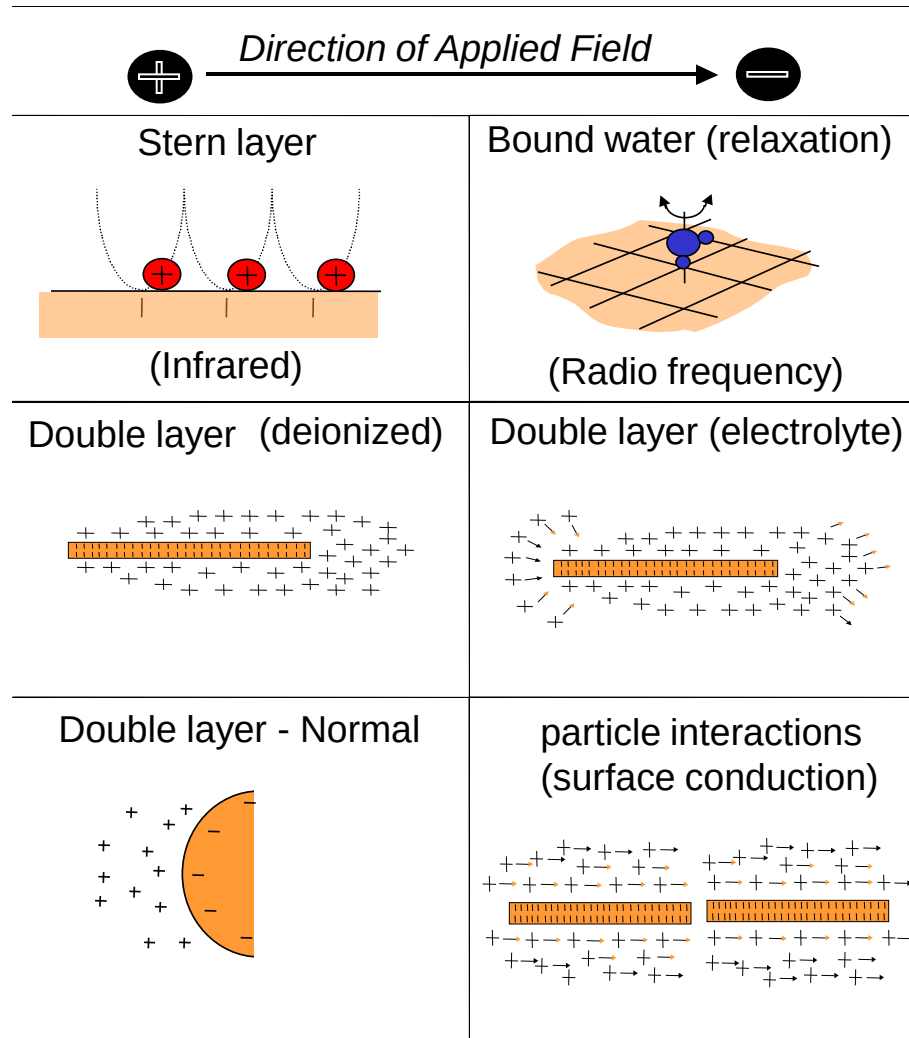
Polarization spectrum



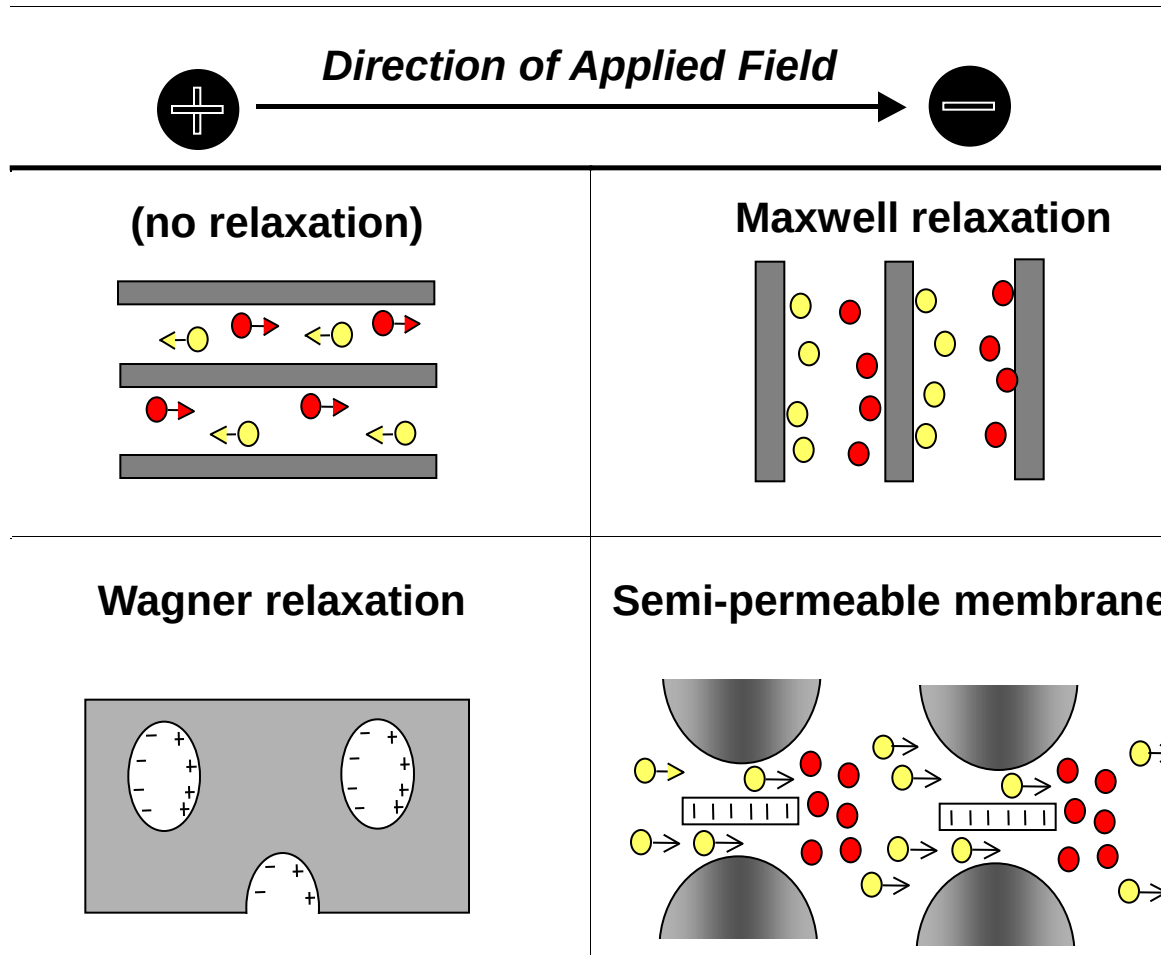
Water-Ion Interaction



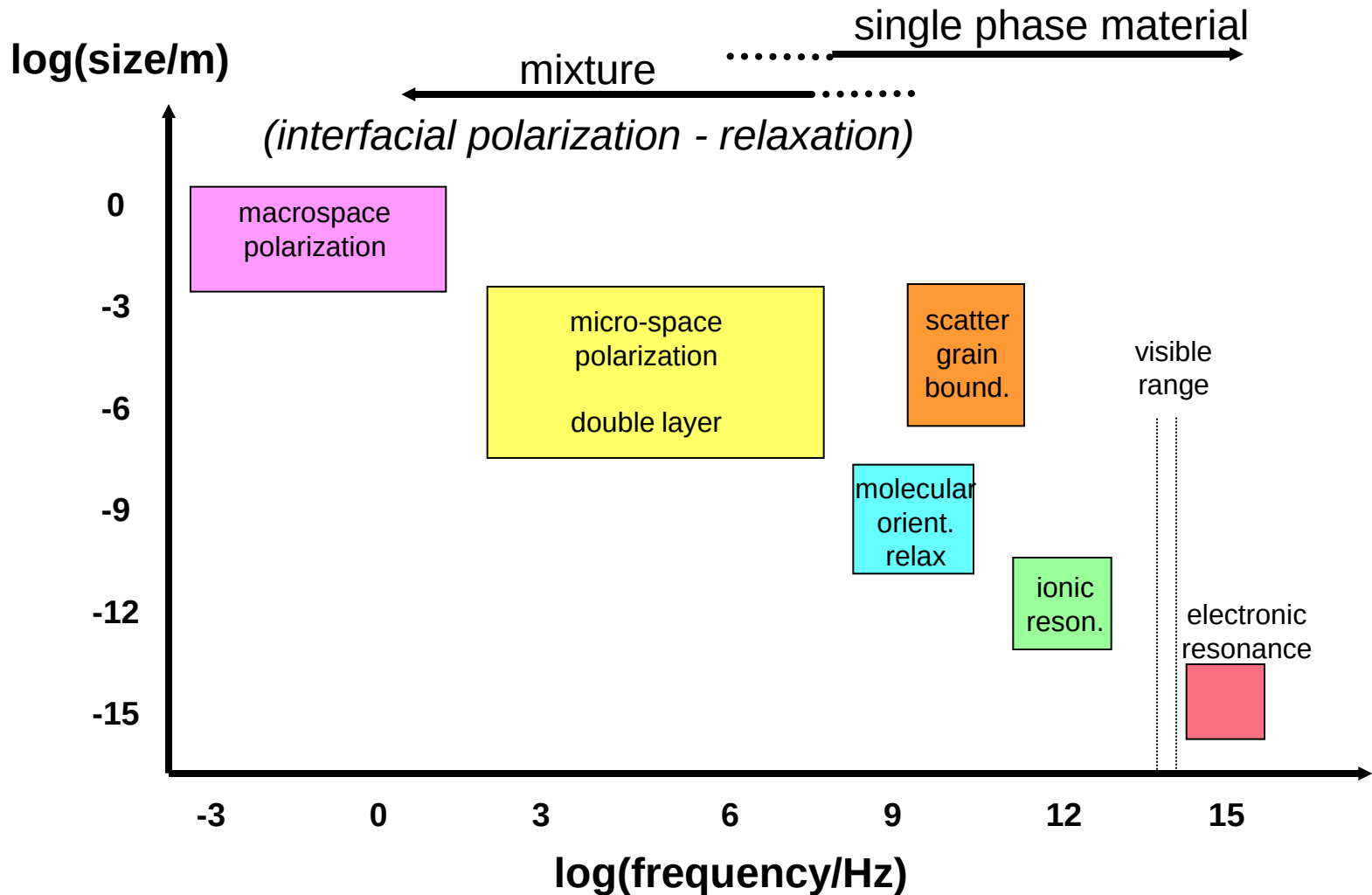
Double layer effects



Two-phase media - Spatial polarization



Polarizations



Summary: Relative Permittivity

water 78			
ice	~3	air, gasses	~1
most organic fluids	2-6	minerals	5-10

$$\kappa'_{soil} = (1-n) \kappa'_m + n(1-S) + nS\kappa'_w$$

Linear mixture

$$\kappa'_{soil} = \left[(1-n) \sqrt{\kappa'_m} + n(1-S) + nS\sqrt{\kappa'_w} \right]^2$$

CRIM

$$\kappa'_{soil} = 3.03 + 9.3\theta_v + 146.0\theta_v^2 - 76.7\theta_v^3$$

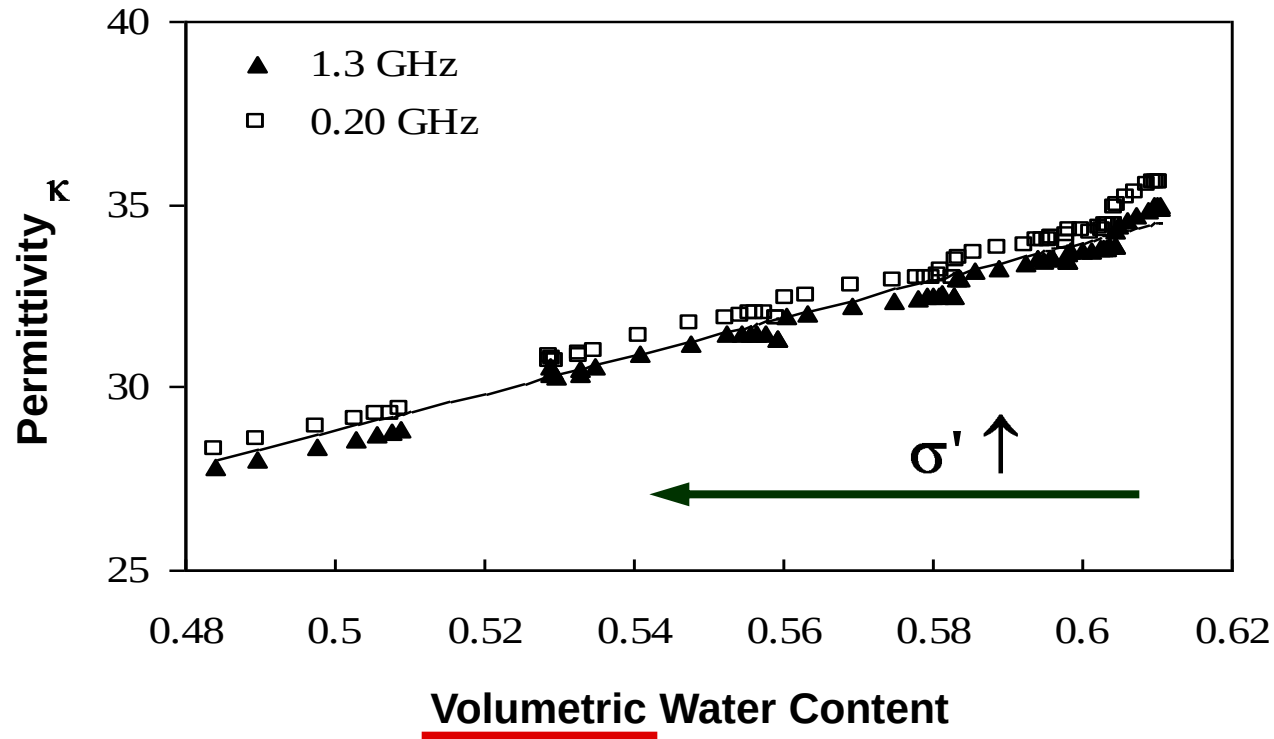
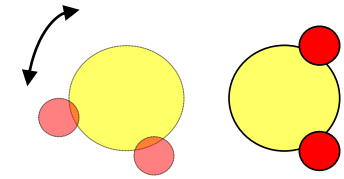
Topp et al. 1980

Summary: Single materials

water	78.5	quartz	4.2 - 5
methanol	32.6	calcite	7.7 - 8.5
most organic fluids	2 - 6	most minerals	6 – 10

Free Water - Consolidation

Orientational Pol.



Summary: Soils

VOLUMETRIC WATER CONTENT

$$\kappa' = 2.6 - 1.6n + 7.9\theta_v^2$$

$$\kappa' = 40\theta_v - 3.9 + \sqrt{44.8 - 392\theta_v + 1600\theta_v^2}$$

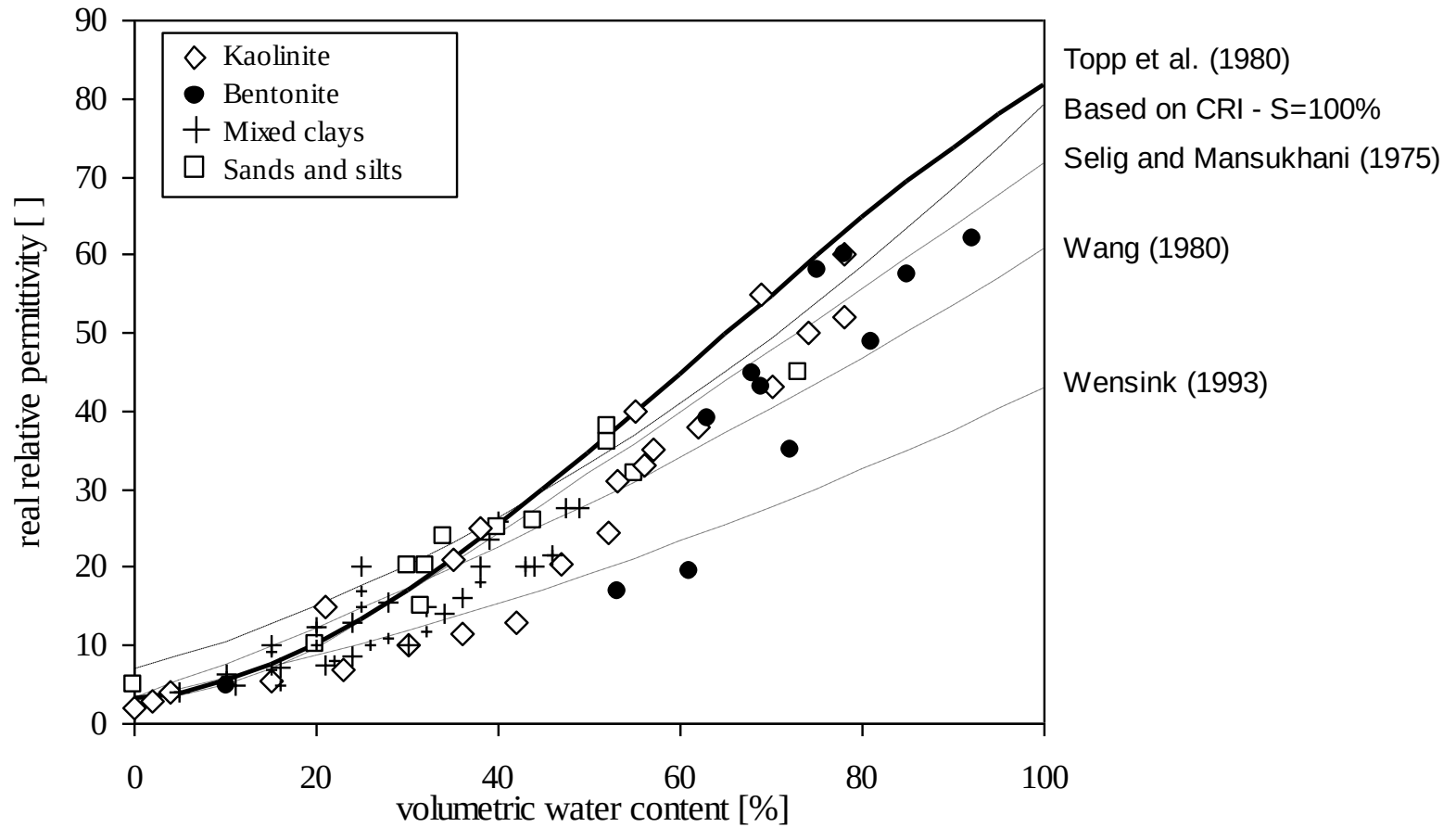
$$\kappa' = 1.40 + 87.6\theta_v - 18.7\theta_v^2$$

$$\kappa' = 3.03 + 9.3\theta_v + 146.0\theta_v^2 - 76.7\theta_v^3$$

$$\kappa' = 3.14 + 23.8\theta_v + 16.0\theta_v^2$$

$$\kappa' = 3.3 + 41.4\theta_v + 16.0\theta_v^2$$

Summary



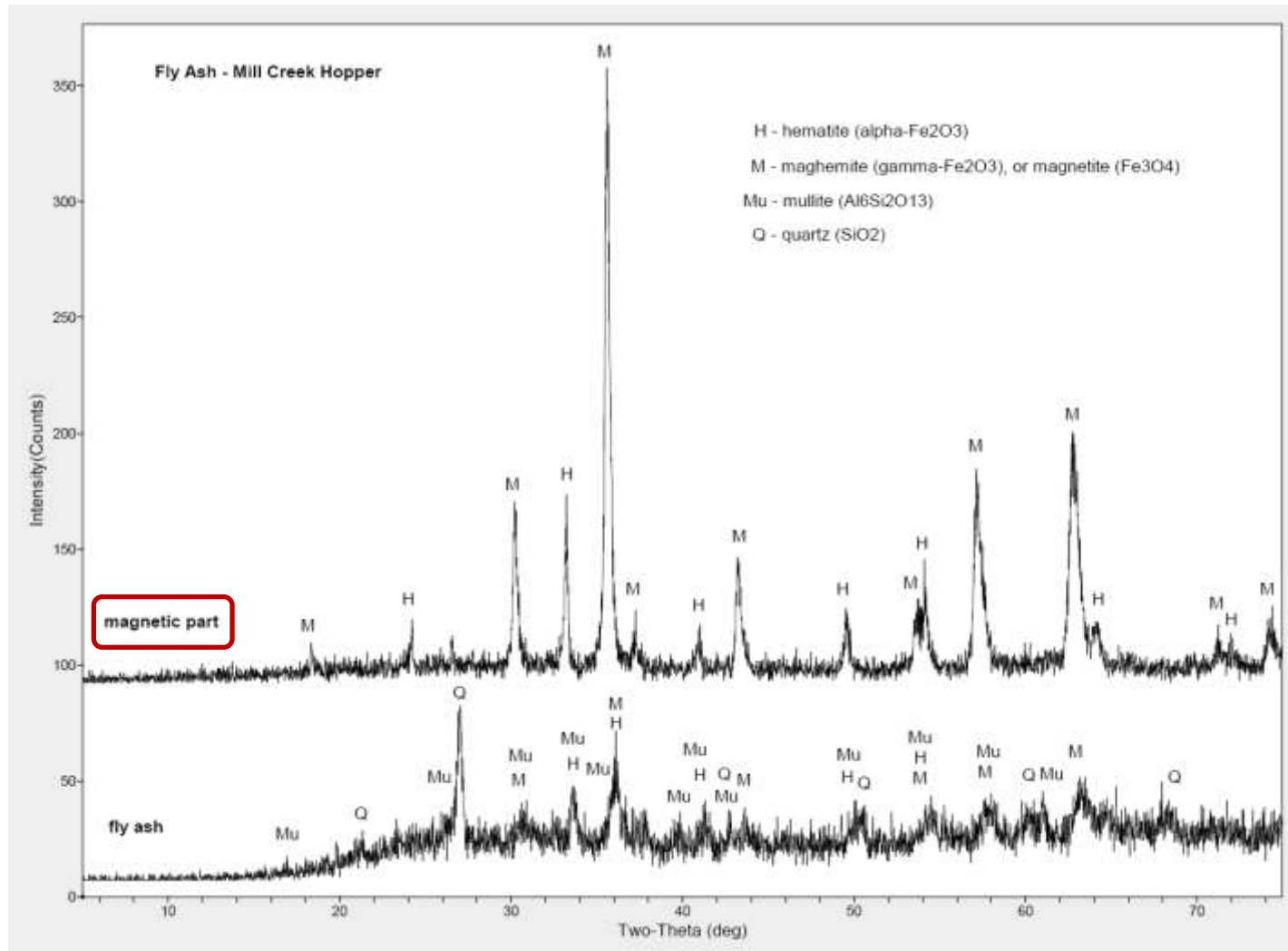
Permeability → Magnetizability

Kingston Fossil Plant (12/22/2008)



[Photo: U.S. Environmental Protection Agency]

XRD: Mill Creek Hopper

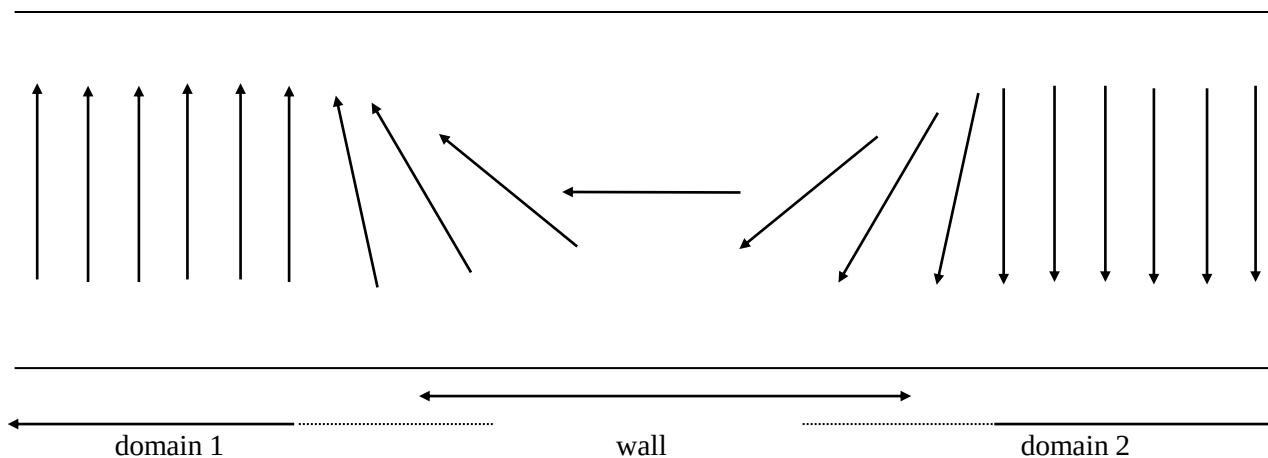


Magnetically separated fraction:

hematite Fe_2O_3 (weakly magnetic), magnetite Fe_3O_4 and maghemite Fe_2O_3 (both strongly magnetic).

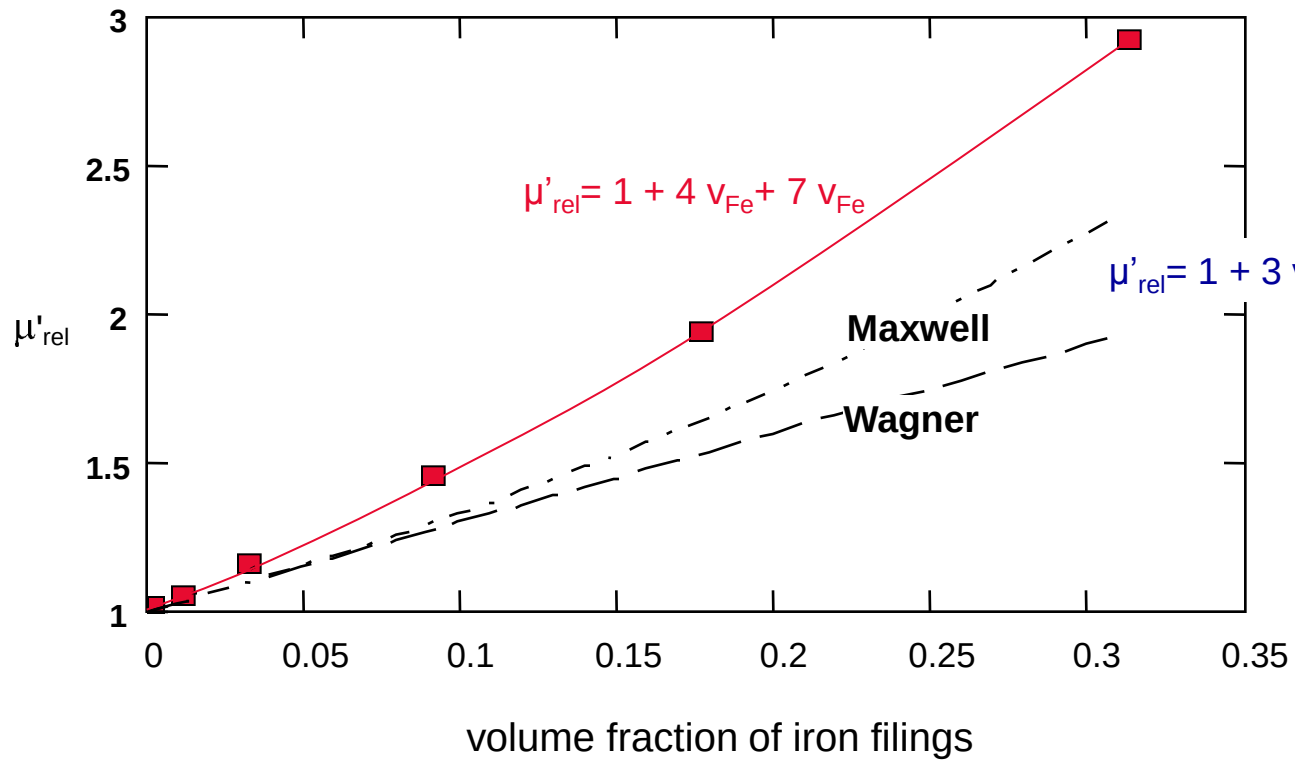
Magnetization

Electron orbits	orbit alignment	Diamagnetism
Electron spin	unpaired	Paramagnetism
Alignment within domains	move domain walls	Ferromagnetism

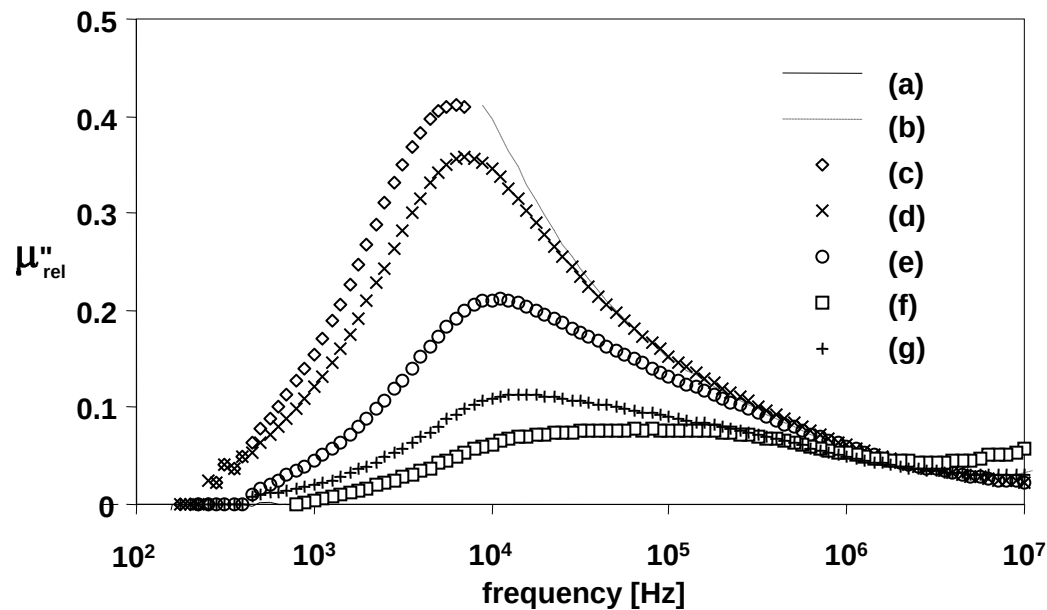
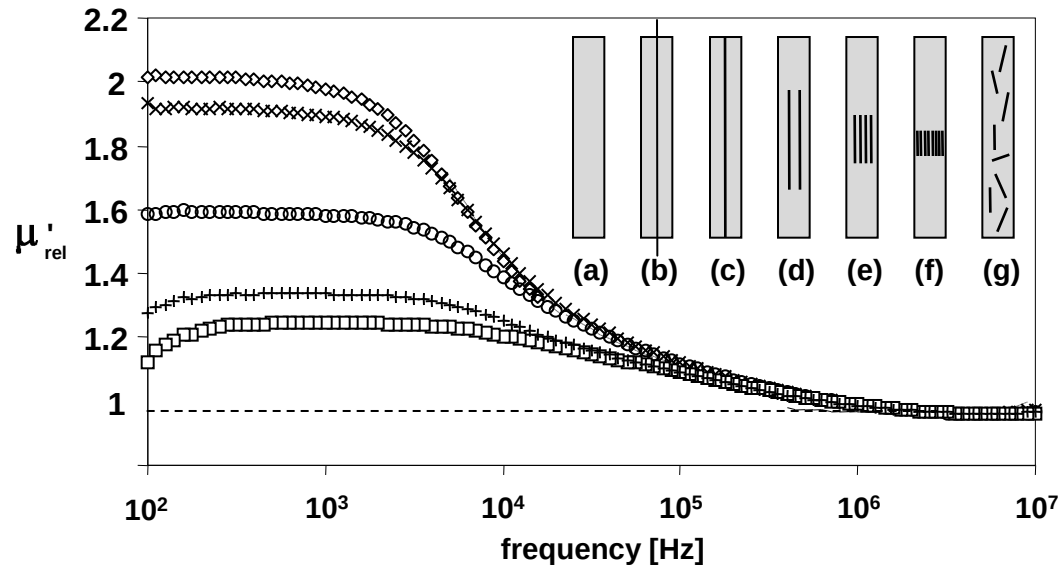


Permeability

iron fillings in kaolinite – $f = 10$ kHz



iron in kaolinite – $f = 10$ kHz

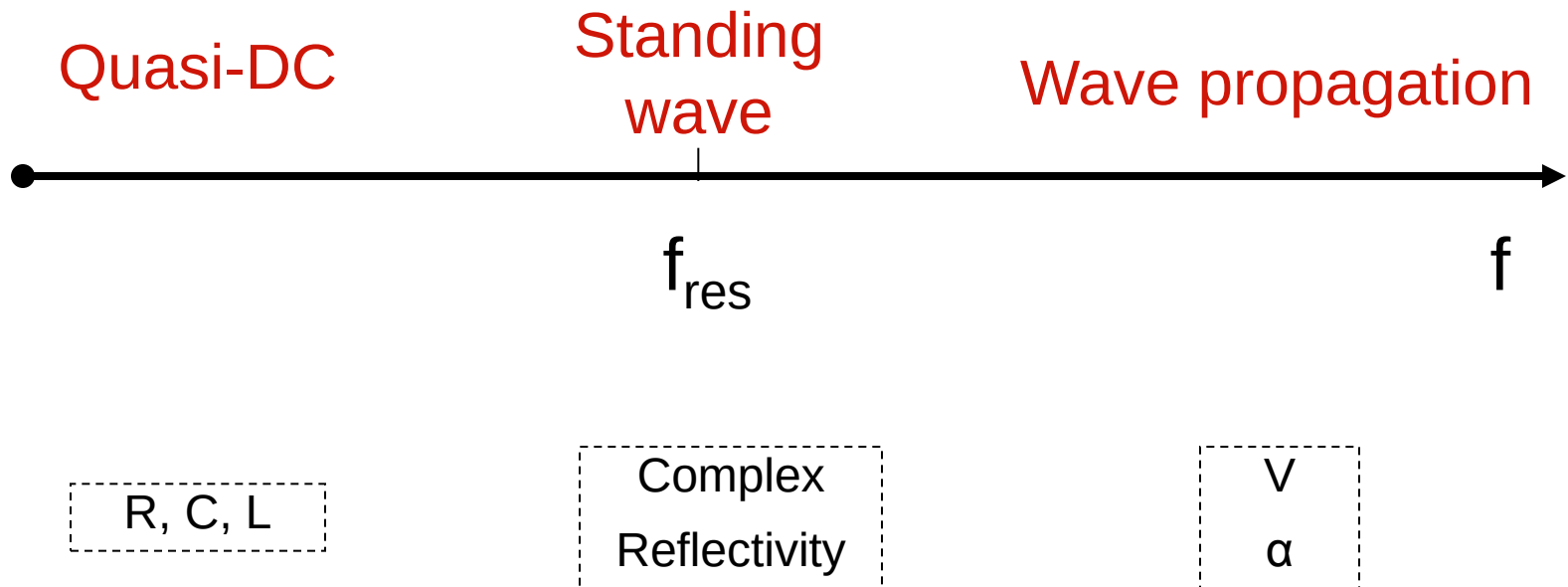


Summary

Single materials	μ'/μ_o
water, quartz, kaolinite (diamagnetic)	~ 0.9999
montmorillonite, illite, granite, hematite (paramagnetic)	$1.00002-1.0005$
nickel, iron (ferromagnetic)	> 300
Predictive relations	
spherical ferromagnetic inclusions	$1 + 3v_{Fe}$ for $v_{Fe} < 0.2$
Kaolinite with iron filings (at 10 kHz)	$1 + 4v_{Fe} + 7v_{Fe}^2$ for $v_{Fe} < 0.3$

Measurement

Testing



Quasi-static

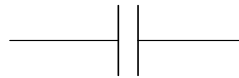
Circuit Elements - Impedance

Resistor (R)



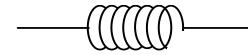
$$\frac{V}{i} = R$$

Capacitor (C)



$$\frac{V}{i} = -j \frac{1}{\omega C}$$

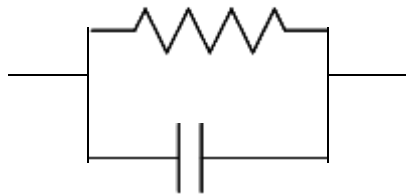
Inductor (L)



$$\frac{V}{i} = j\omega L$$

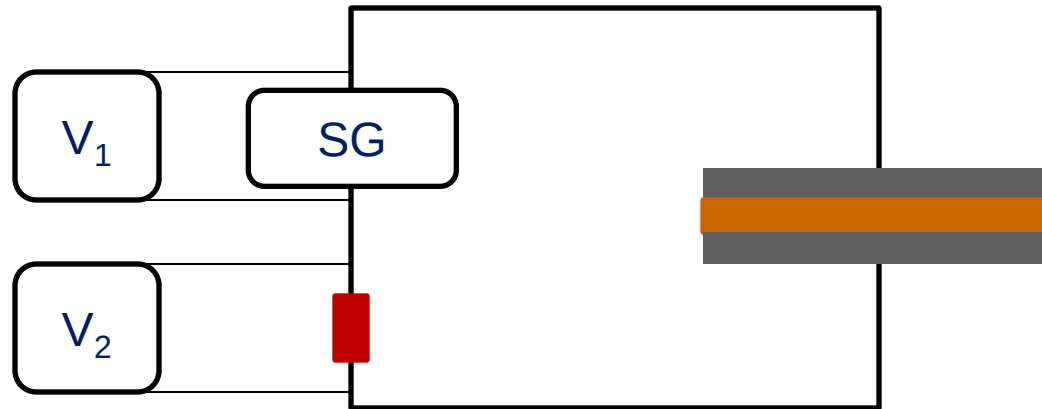


$$Z^* = \frac{V}{i} = R + j \left(\omega L - \frac{1}{\omega C} \right)$$

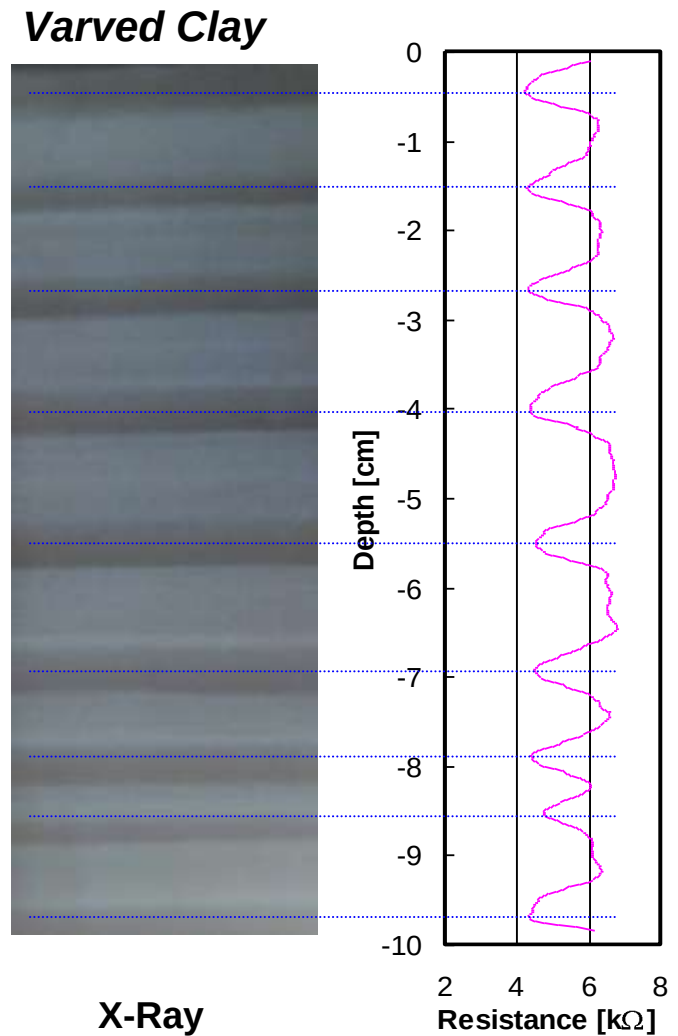
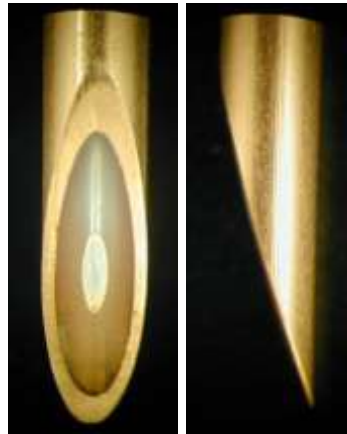
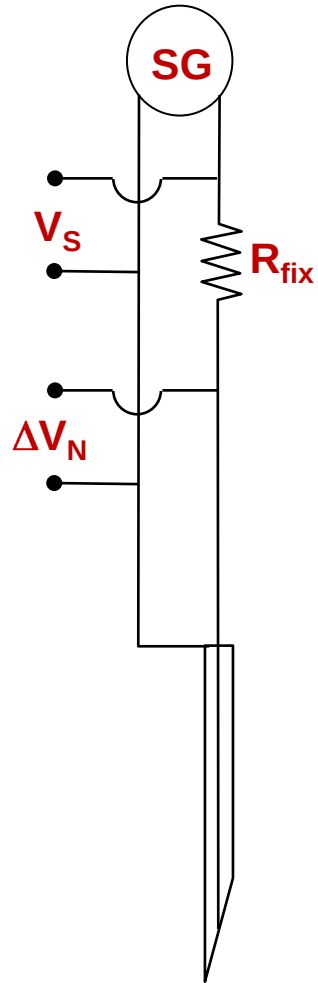


$$Z^* = \frac{V}{i} = \frac{1}{\frac{1}{R} + j\omega C}$$

Laboratory measurements



Laboratory: Electrical Needle



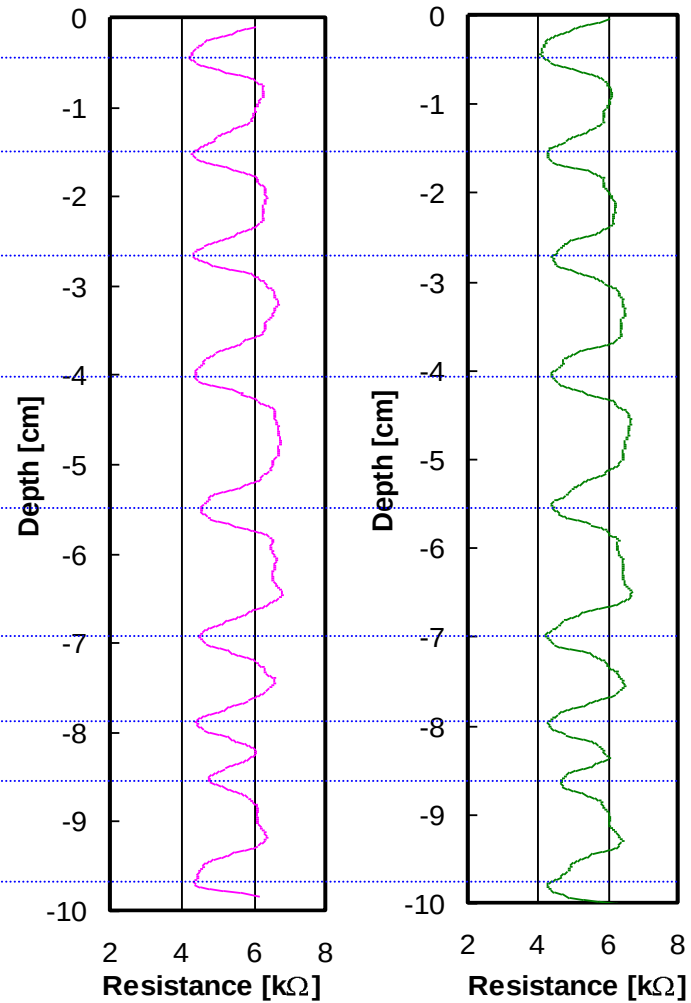
Lab-scale



X-Ray



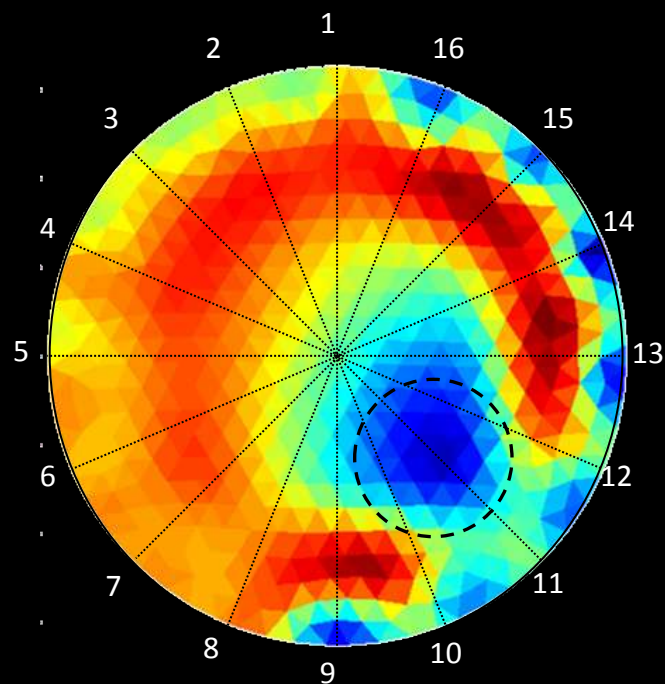
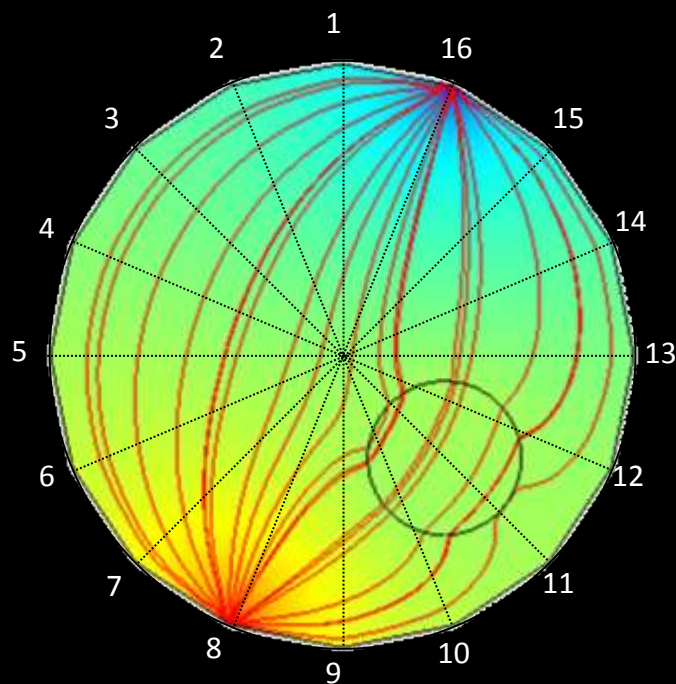
Photograph



Needle probe measurements

Numerical and Experimental Study

high conductivity anomaly

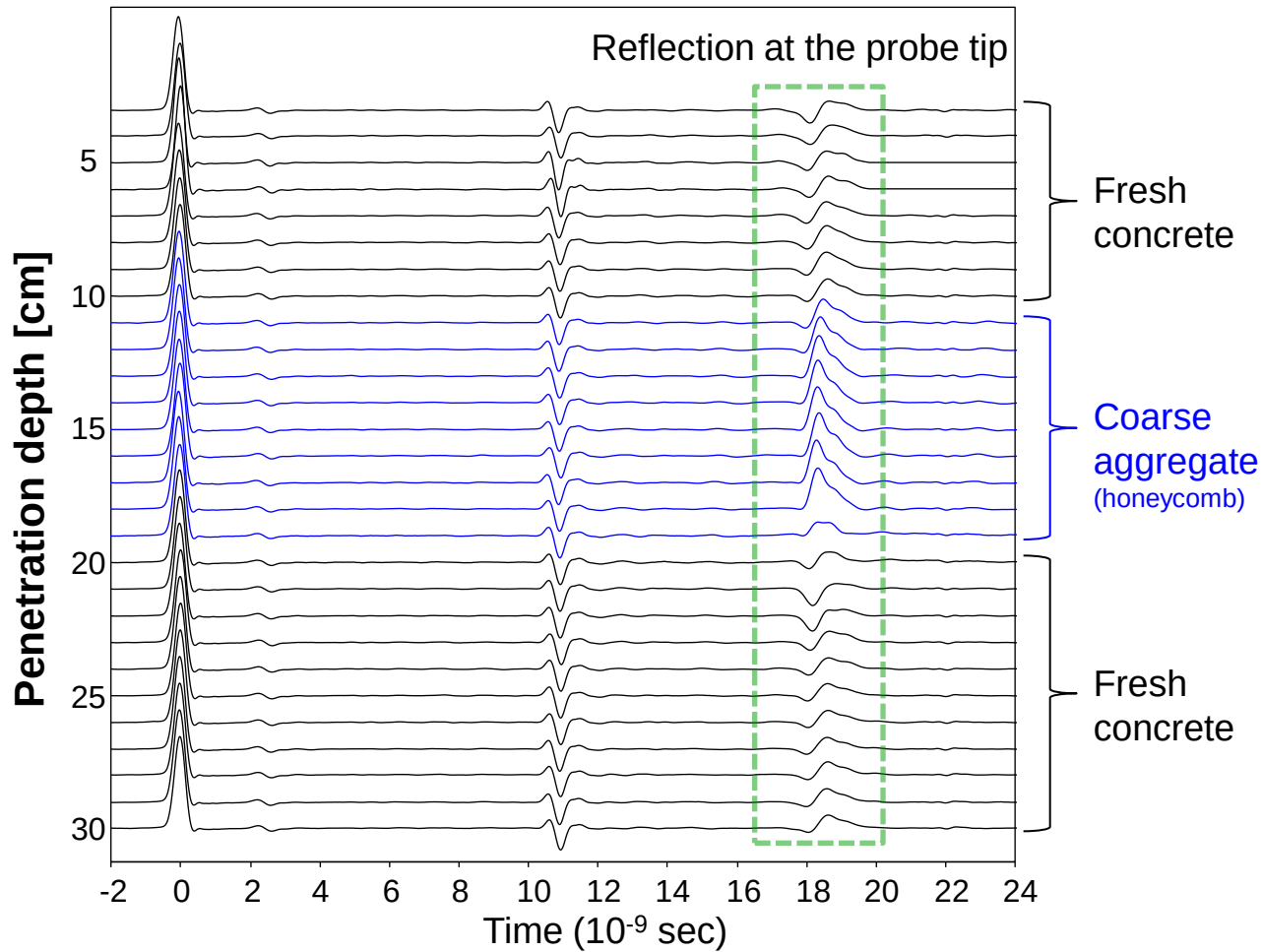


WAVE PROPAGATION

Laboratory measurements



TDR Probe – Honeycombs



Cone in TDR-mode

Field Devices

Typical Data

Resistivity measurement / imaging

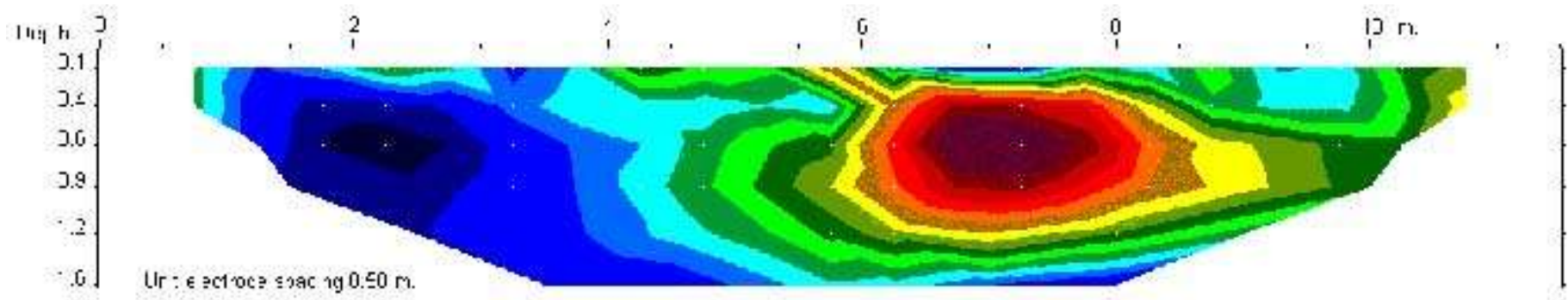
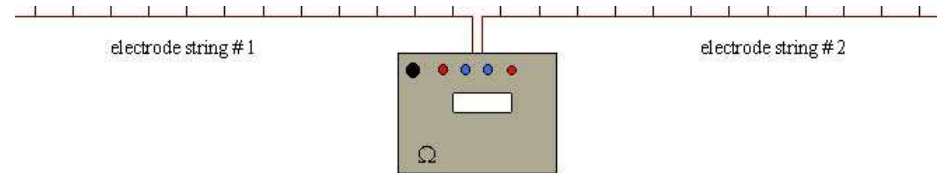


Syscal Kid Switch 24

Resistivity range: 0.001 to 10,000 Ohm meter

Depth less than 70m

Typical pulse duration: ~0.5s to 2s.



EM devices (conductivity)

EM38 Ground Conductivity Instrument

Very shallow ($\sim < 1\text{m}$)

Conductivity range: 100, 1000 mS/m

Frequency 14.6 kHz



EM 34 - Ground Conductivity Instrument

Shallow ($< 60\text{ m}$)

Intercoil spacing and operating frequency: 10m at 6.4 kHz, 20m at 1.6 kHz, 40m at 0.4 kHz

Conductivity Ranges 10, 100, 1000 mS/m



Ground Penetrating Radar

(permittivity ... conductivity and permeability)

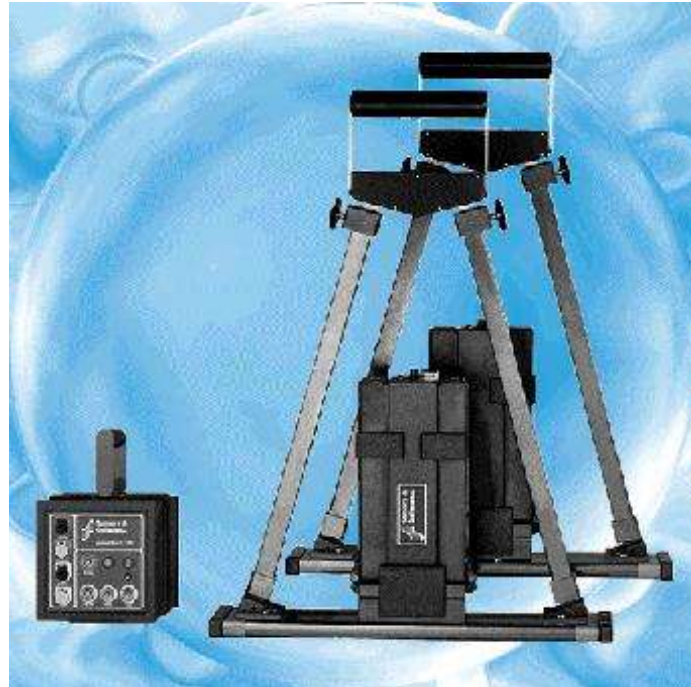
Pulse EKKO 1000

antenna frequencies; 110, 225, 450, 900, 1200 MHz



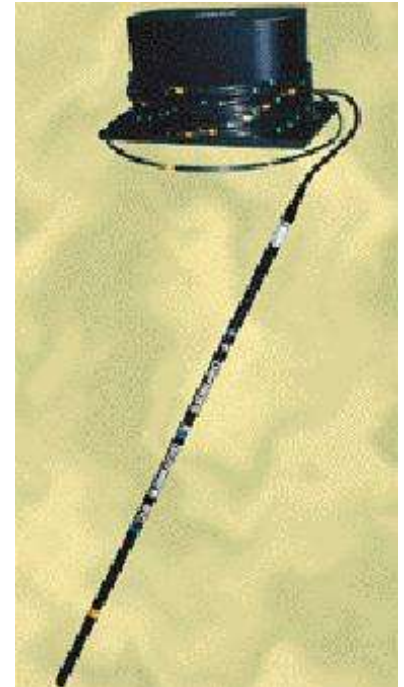
Pulse EKKO 100 antenna

frequencies; 12.5, 25, 50, 100, and 200 MHz (also borehole)

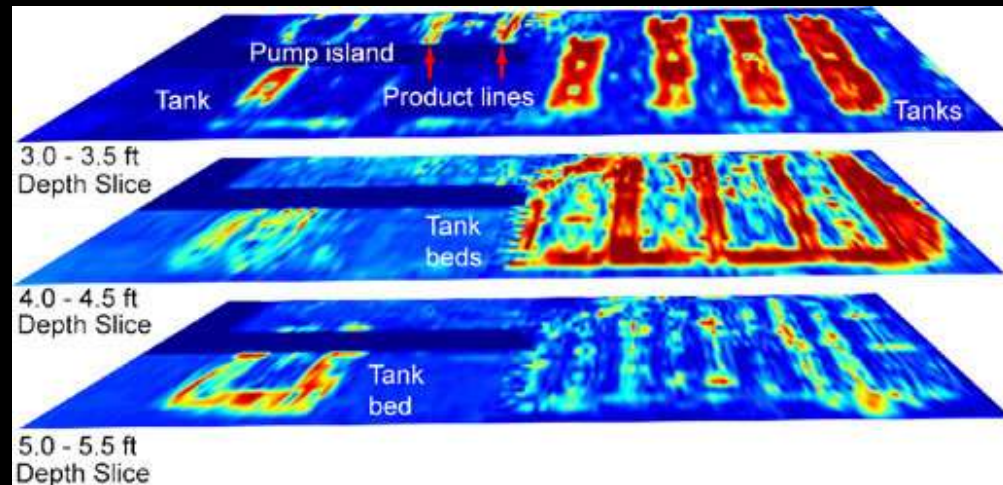
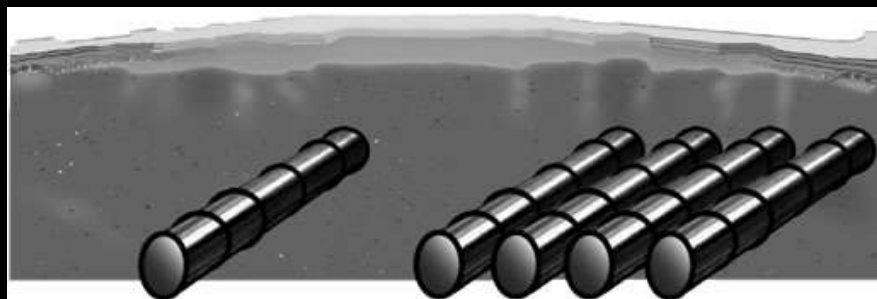
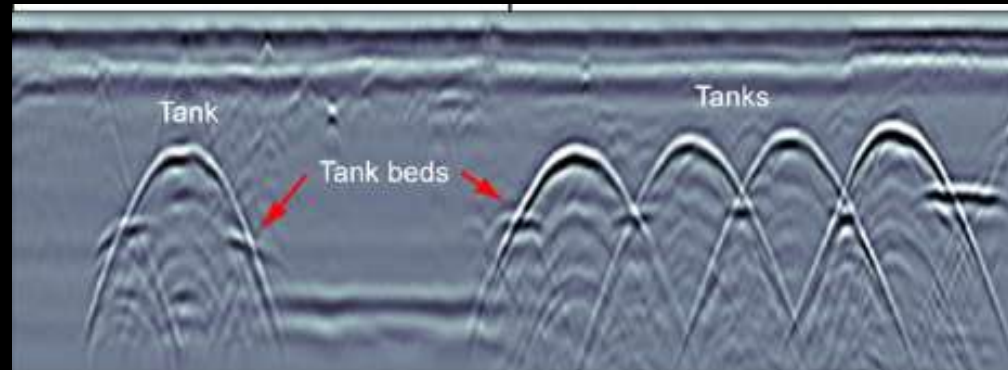


Borehole Antennas

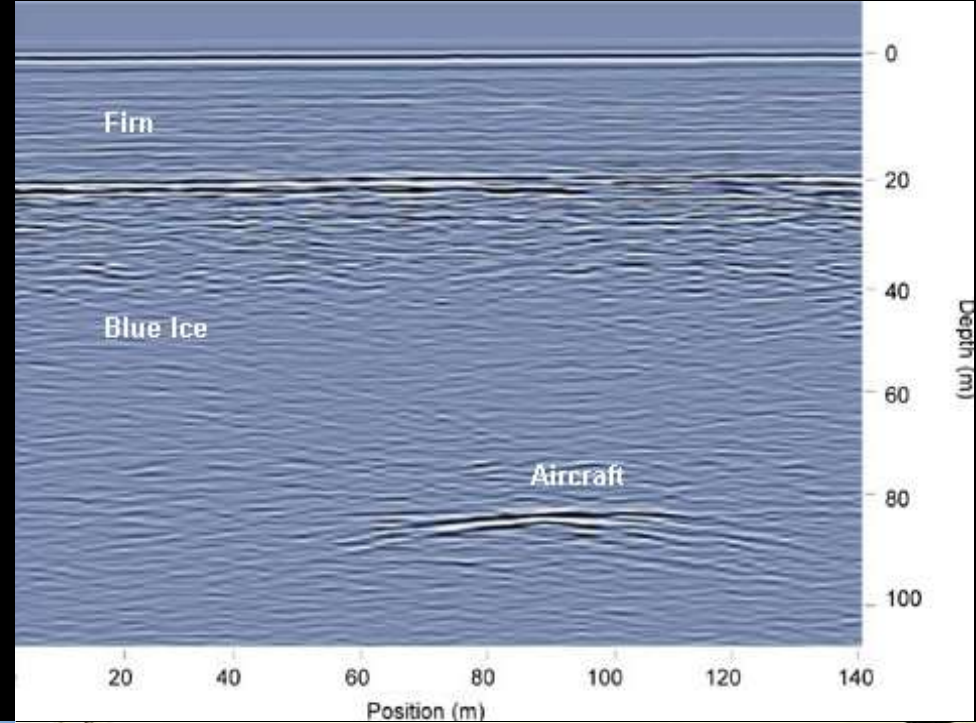
(50, 100, 200 MHz)



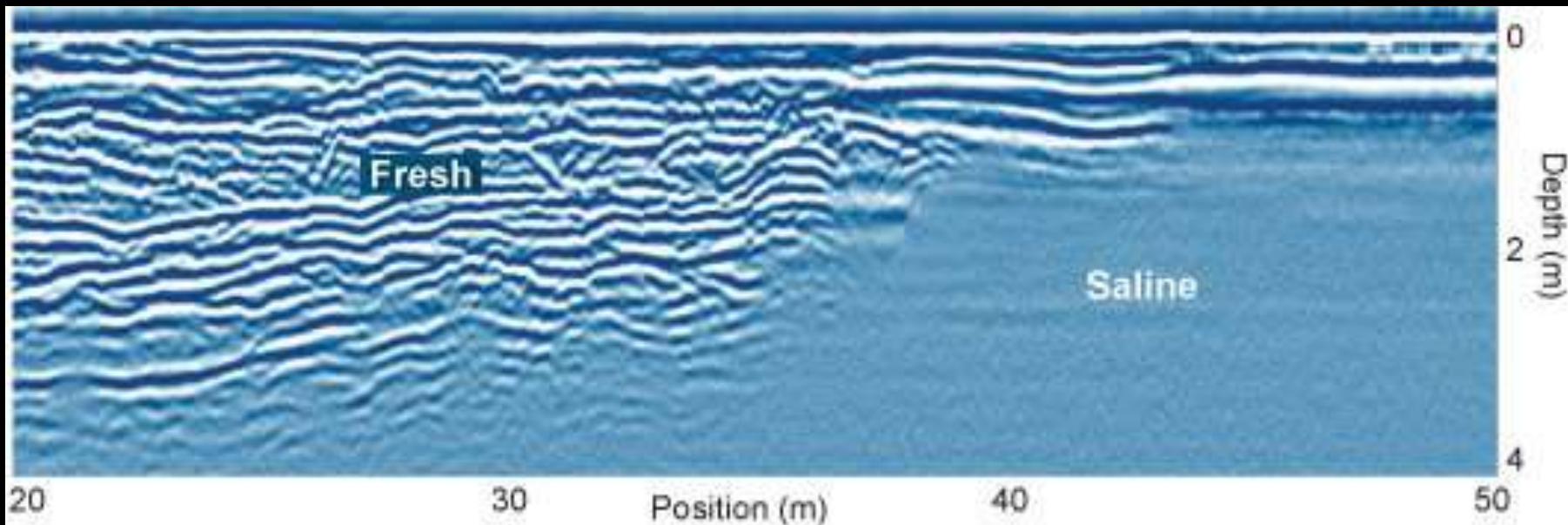
GPR - 2D & 3D



GPR on Ice



GPR: Saltwater Intrusion



Summary: EM-waves

μ	typically non-ferromagnetic caution otherwise (e.g., some mine waste, fly ash)	
σ	ionic concentration ... and mobility fresh water: clay surface conduction Simple measurement: ERT, Needle Probe (<i>invasive</i>)	
κ	free water orientation (microwave frequency) GPR TDR probe (<i>invasive</i>)	
V S_d	$V \downarrow$ when $\sigma_{el} \uparrow$ and $\kappa \uparrow$ $S_d \downarrow$ when $\sigma_{el} \uparrow$	
Use	volumetric water content advect./diffus. fluid fronts freezing fronts spatial variability	consolidation salt water intrusion hydrates buried anomalies