Geophysical Characterization

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<u>Mechanical</u> Waves

<u>Electromagnetic</u> Waves

<u>Thermal</u> Phenomena

Processing

description

estimation

lab & field

examples
(process monitoring)

concepts
&
caveats

Mechanical Waves

ρ

D

V_P

V_S

Electromagnetic Waves

Thermal Phenomena

Processing

Wave Equation

Equilibrium

$$\rho \frac{\partial^2 u_x}{\partial t^2} = \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}$$

Constitutive

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \nu\left(\sigma_x + \sigma_y\right)\right] \qquad \gamma_{xy} = \frac{\tau_{xy}}{G}$$

Compatibility

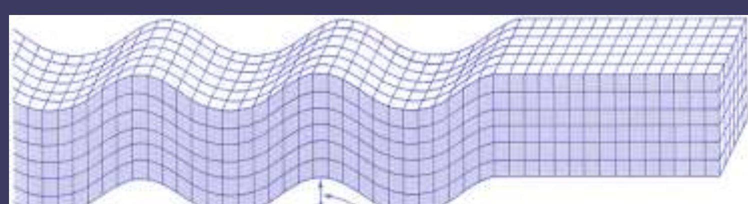
$$\varepsilon_x = \frac{\partial u_x}{\partial x} \qquad \gamma_{xy} = \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}$$

Wave Equation

$$\rho \frac{\partial^2 u_x}{\partial t^2} = (M - G)\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_y}{\partial x \partial y} + \frac{\partial^2 u_z}{\partial x \partial z}\right) + G\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2}\right)$$

Mechanical Waves

$$V_S = \sqrt{\frac{G}{\rho}}$$

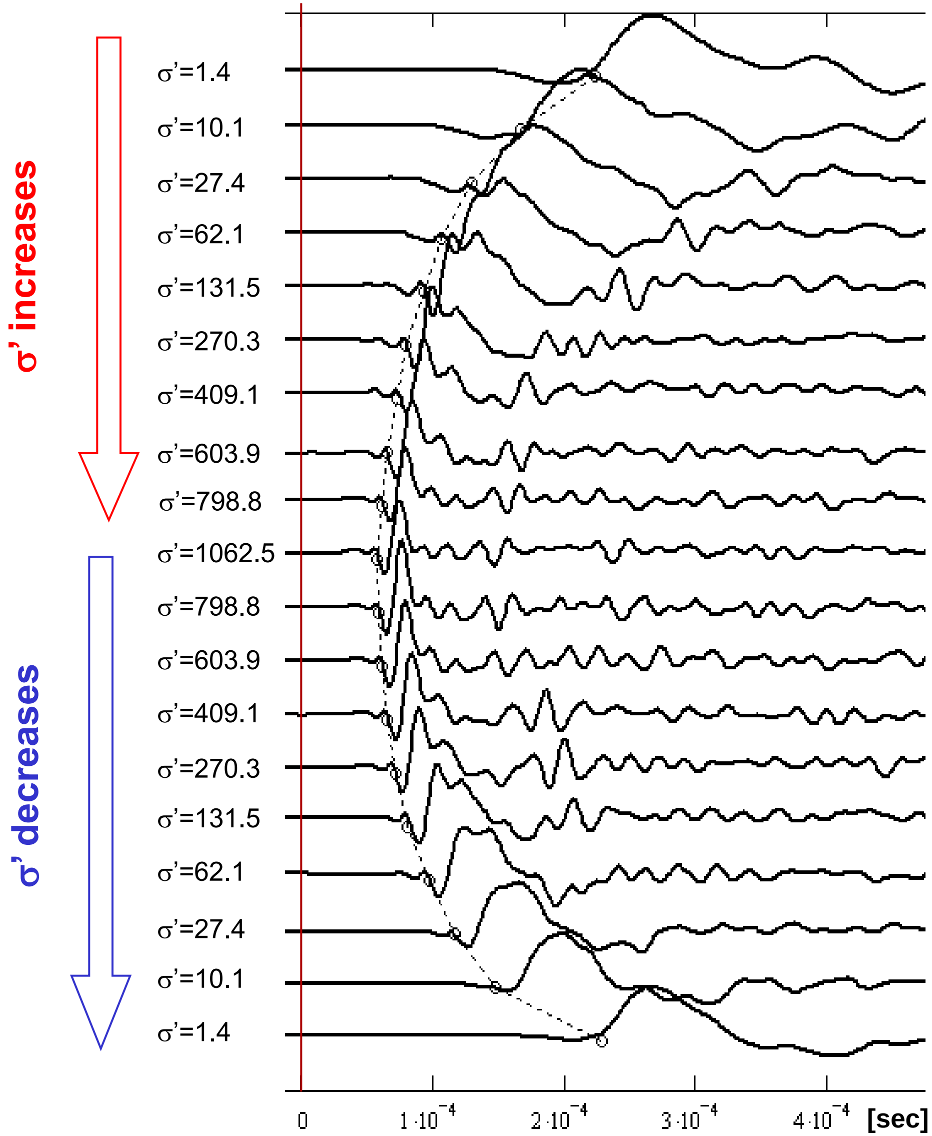


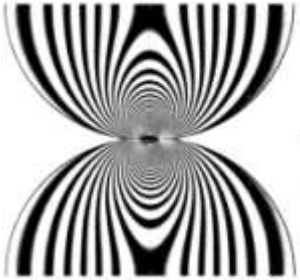
attenuation

S-waves

P-waves

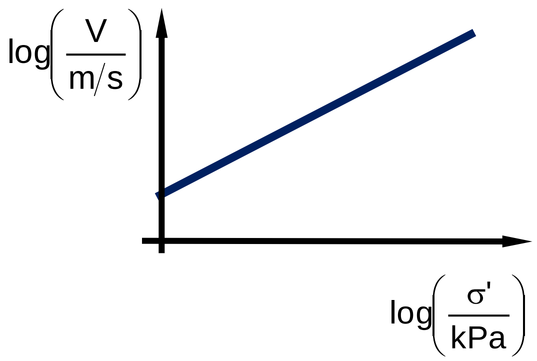
1: Effective Stress

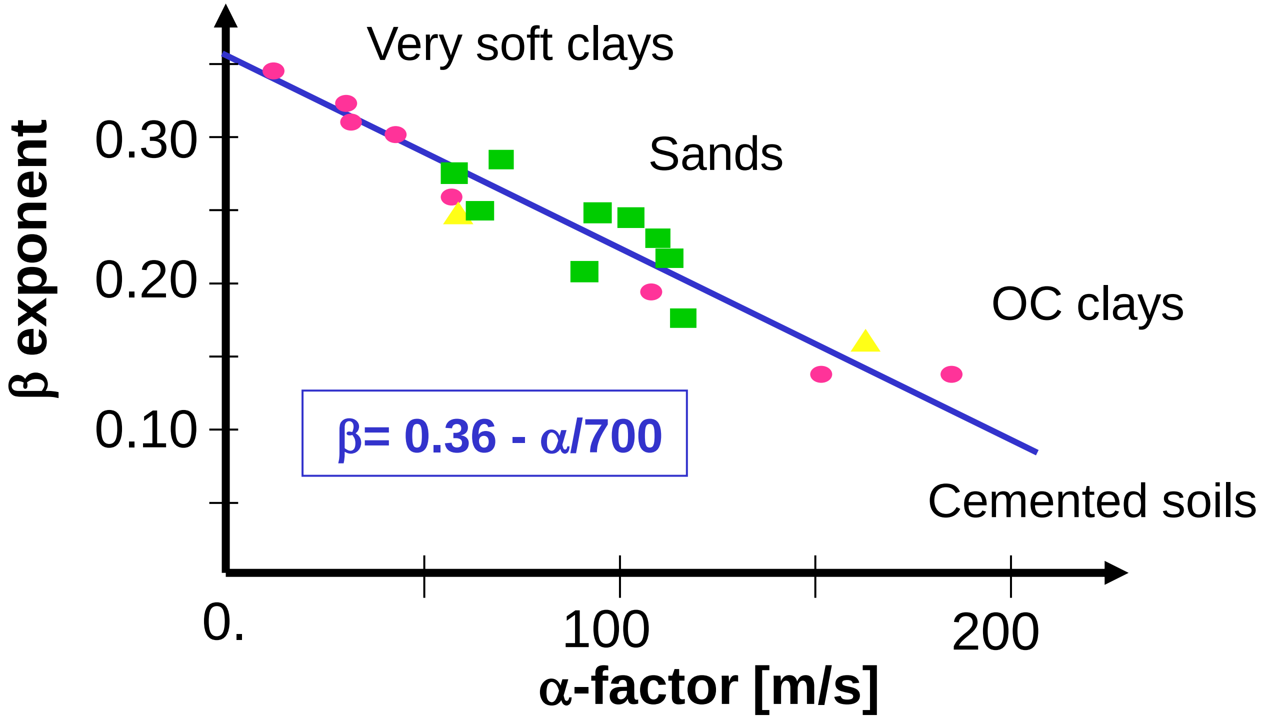




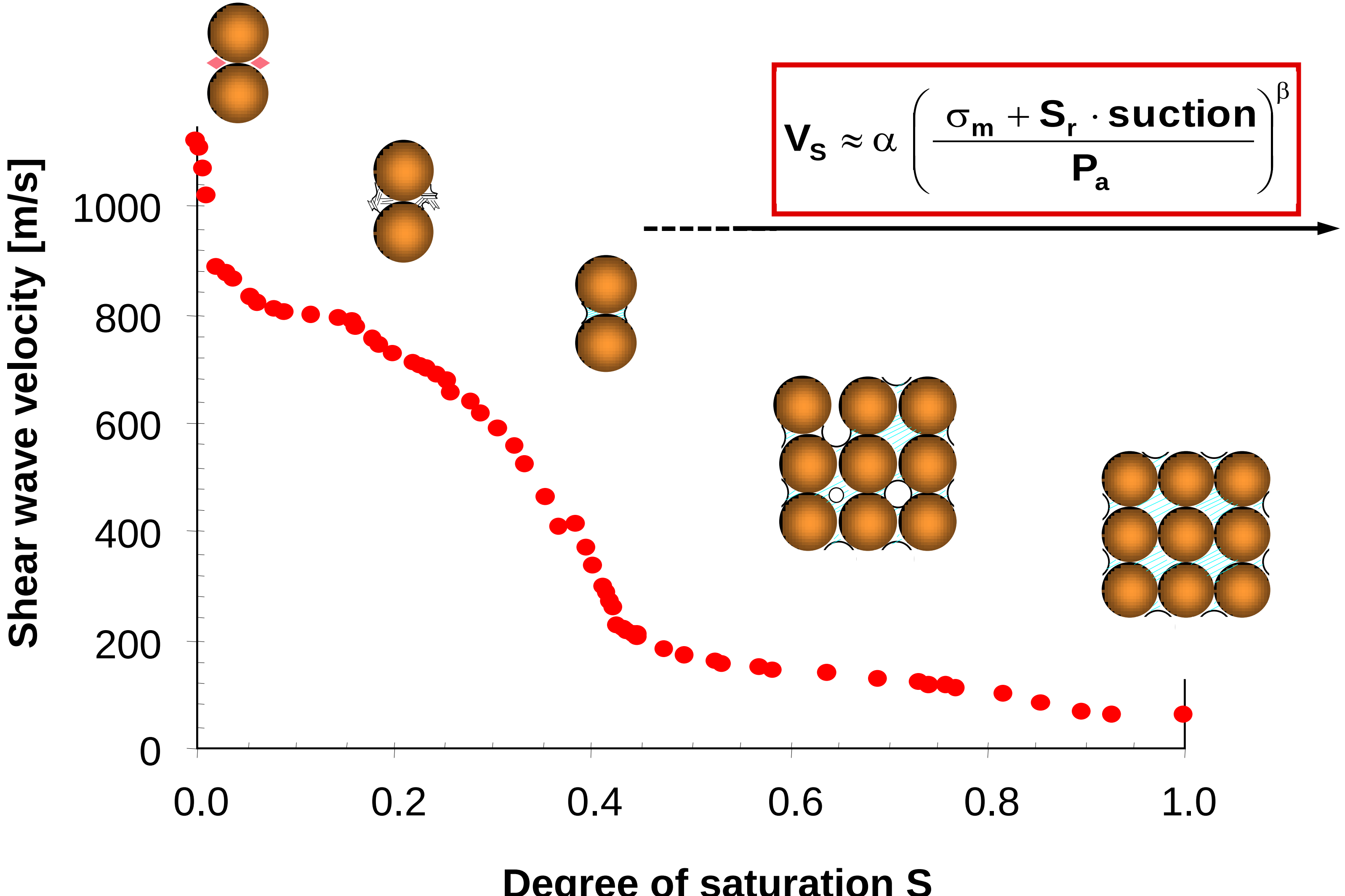
1: Effective Stress

$$V_S = \alpha \left(\frac{\sigma'_x + \sigma'_y}{2 P_a} \right)^{\beta}$$

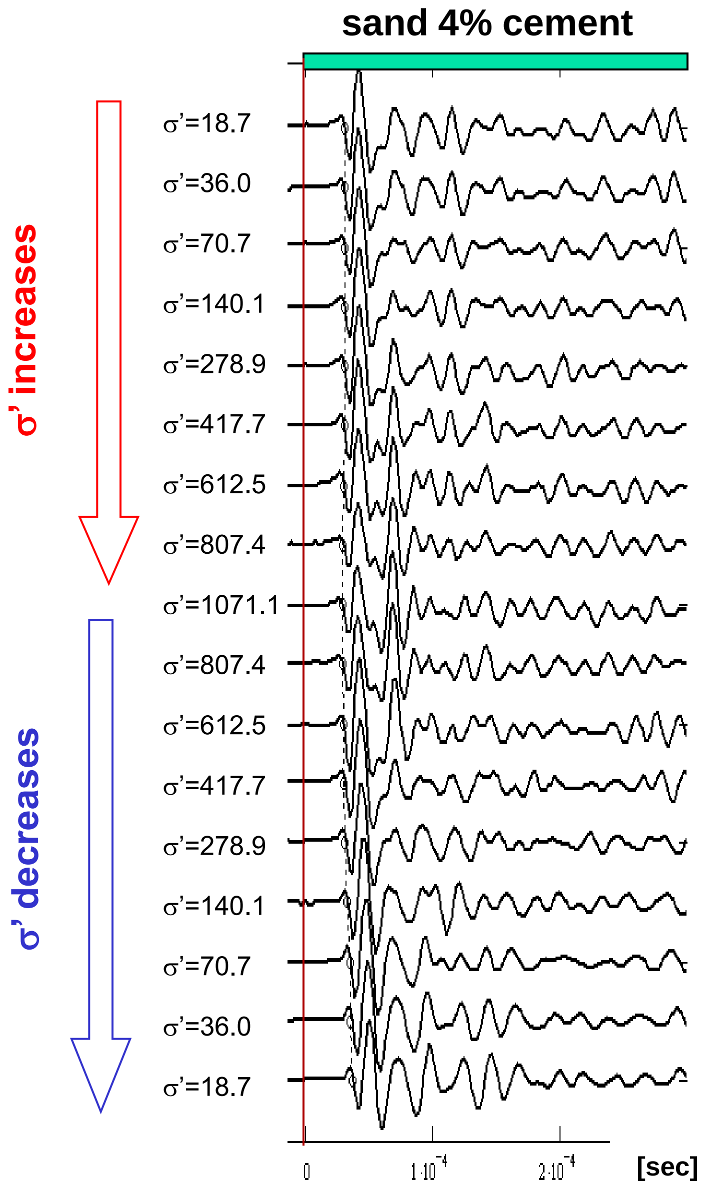


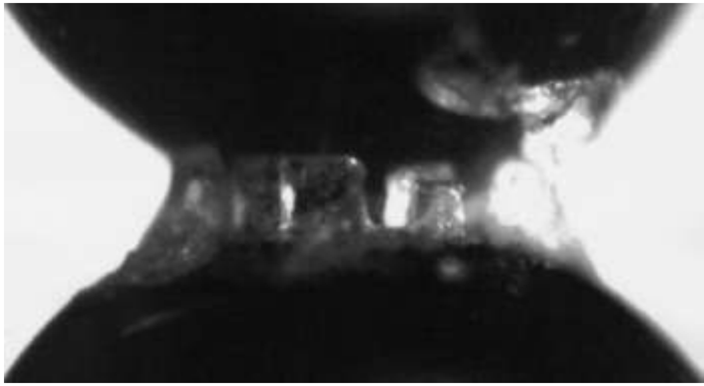


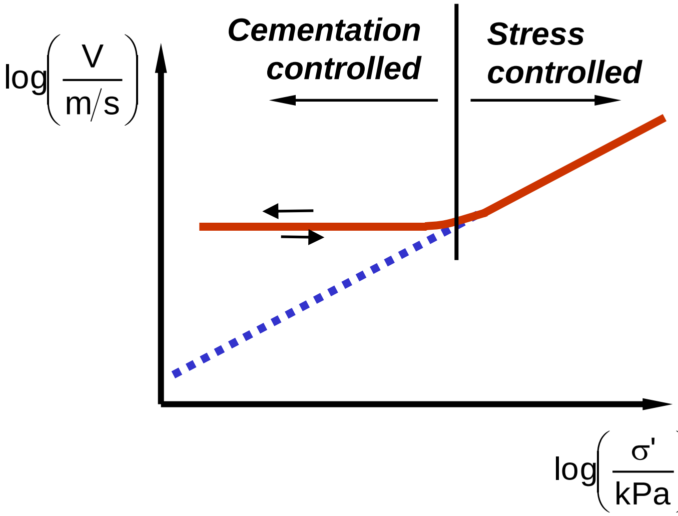
2: Suction - Unsaturated Soils



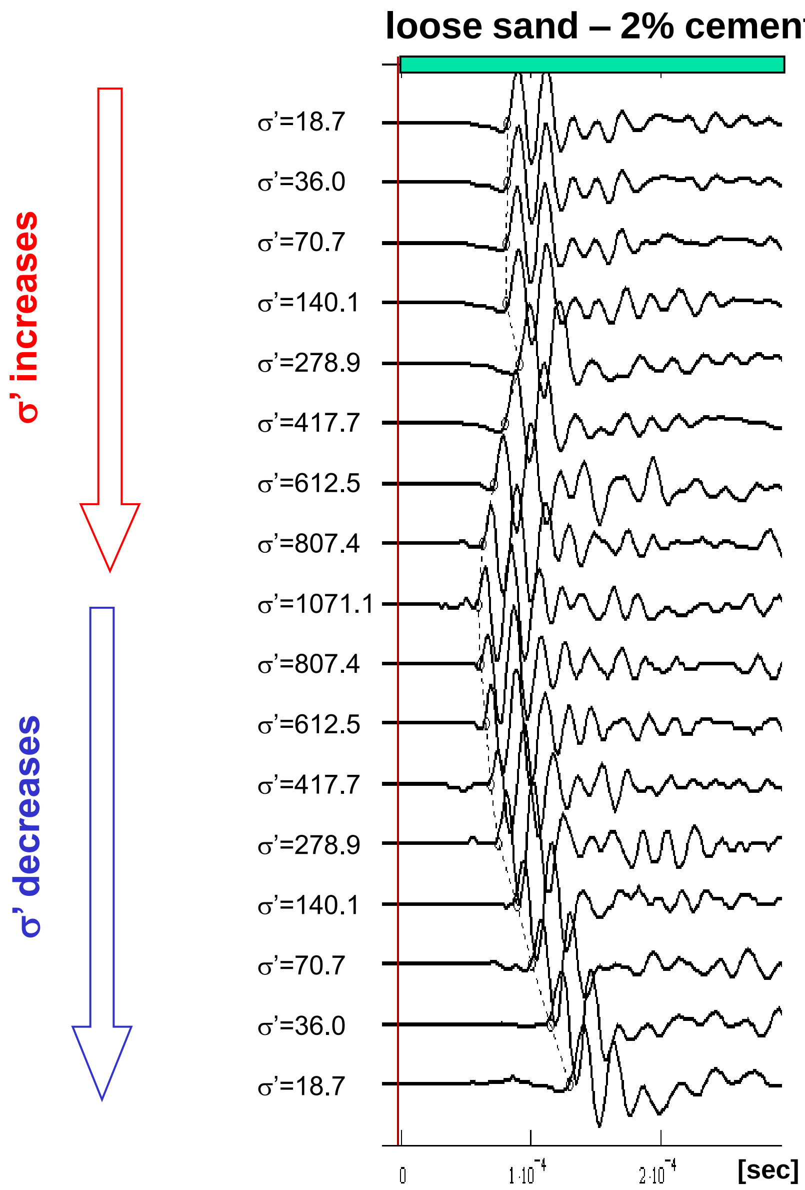
3: Cementation

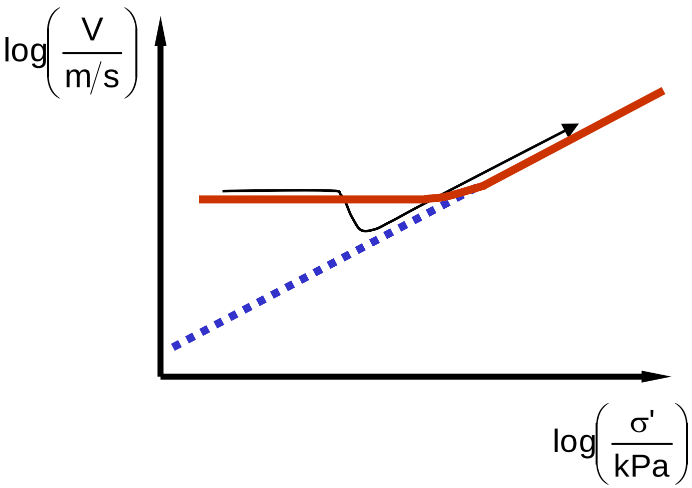






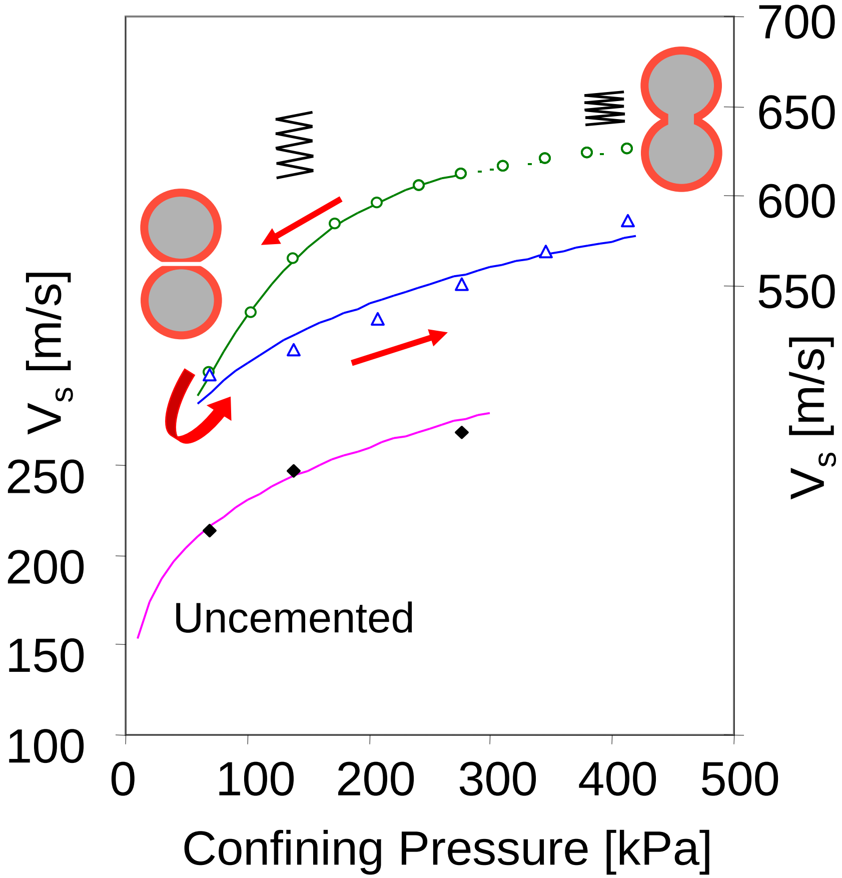
3: Cementation - Loading

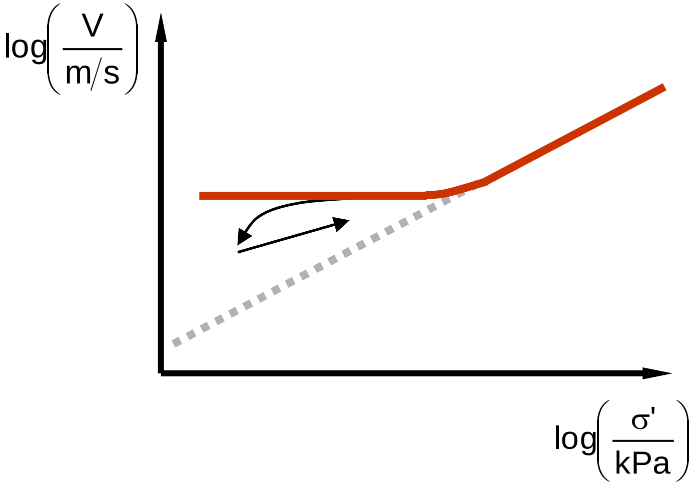




T.Y. Yun

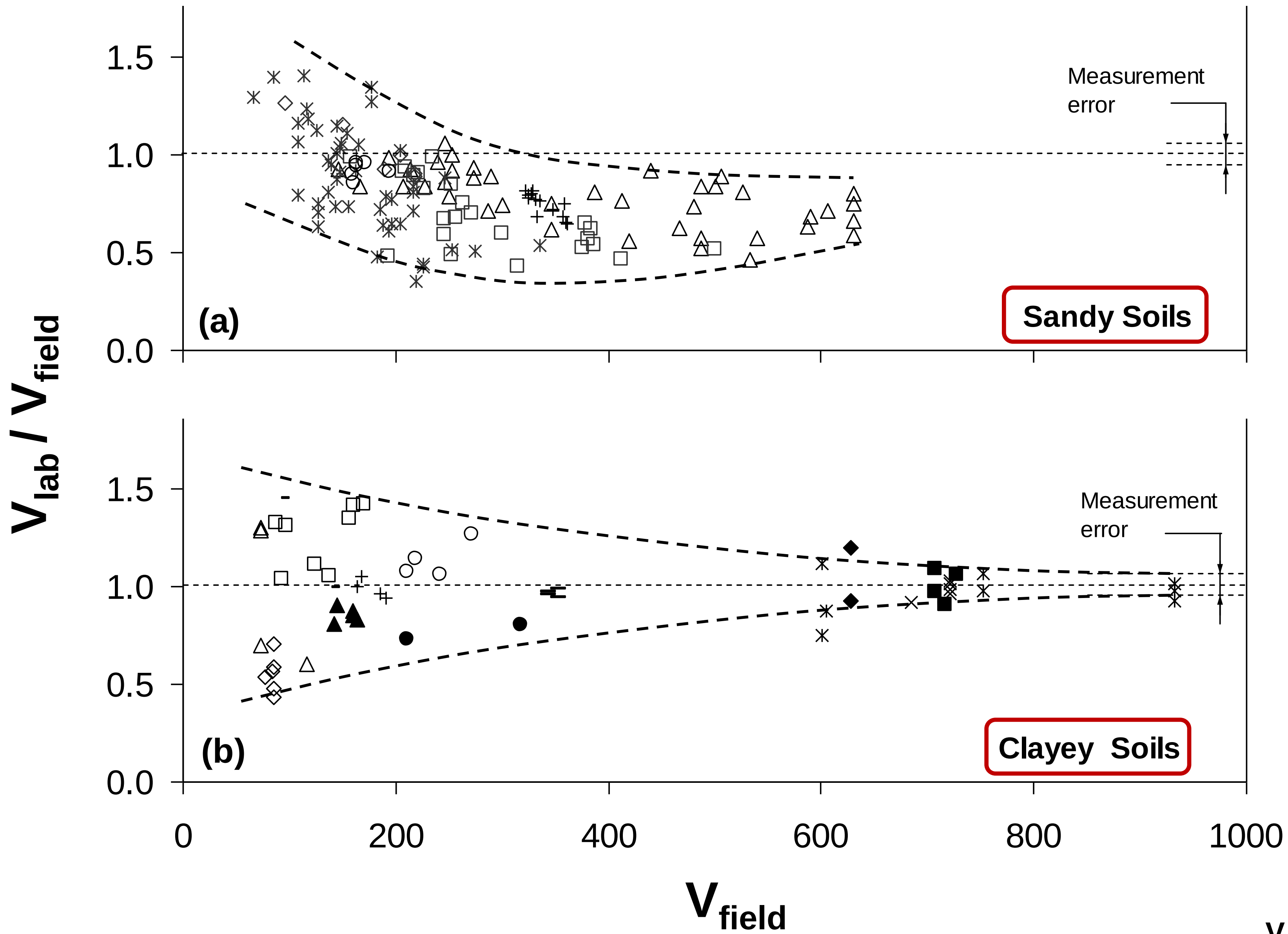
3: Cementation - Unloading





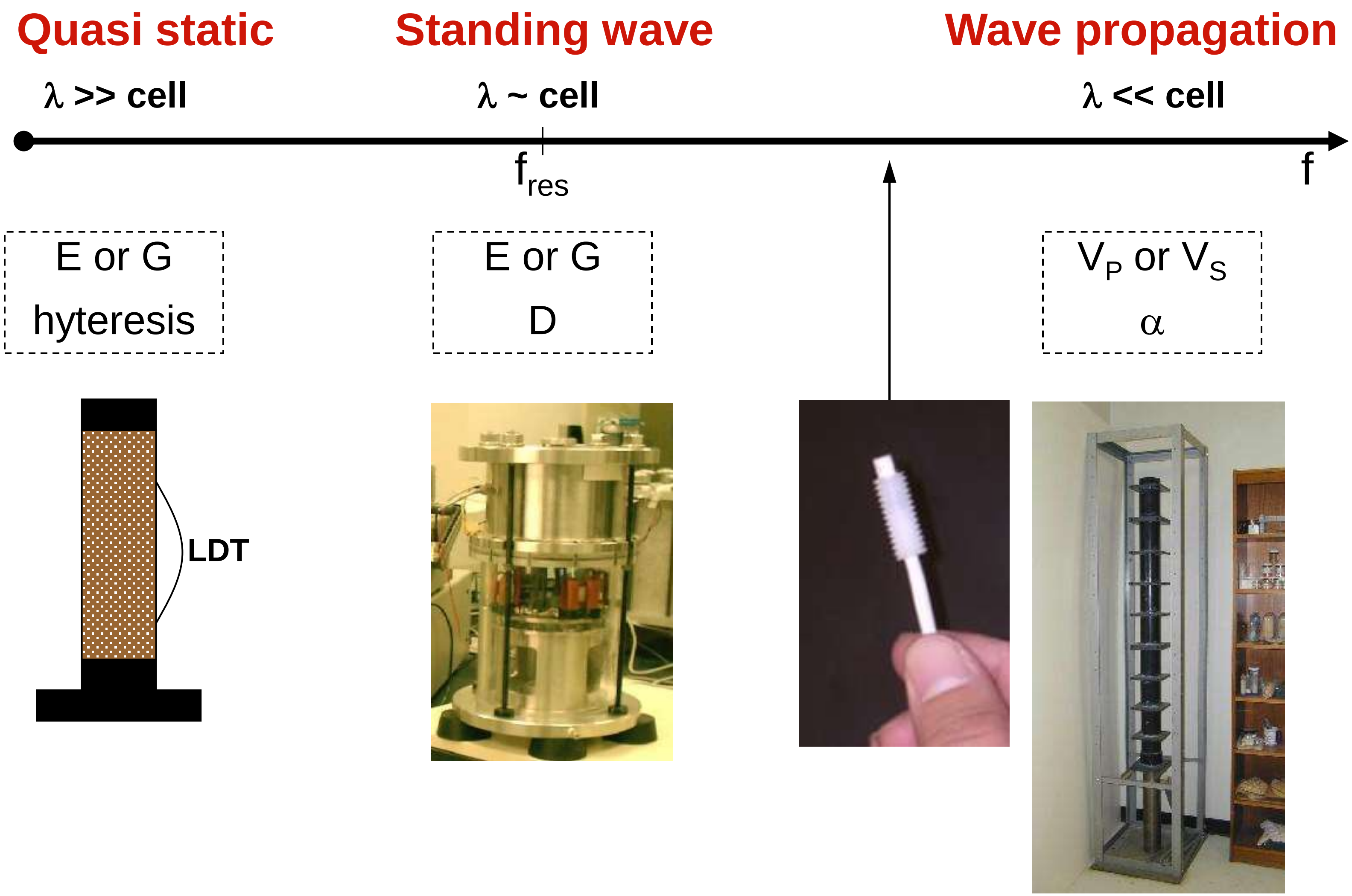
A. Fernandez

3: ➔ Sampling effects

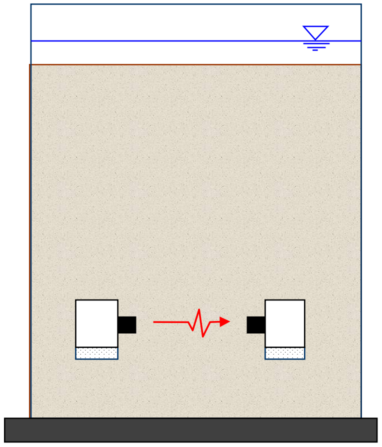


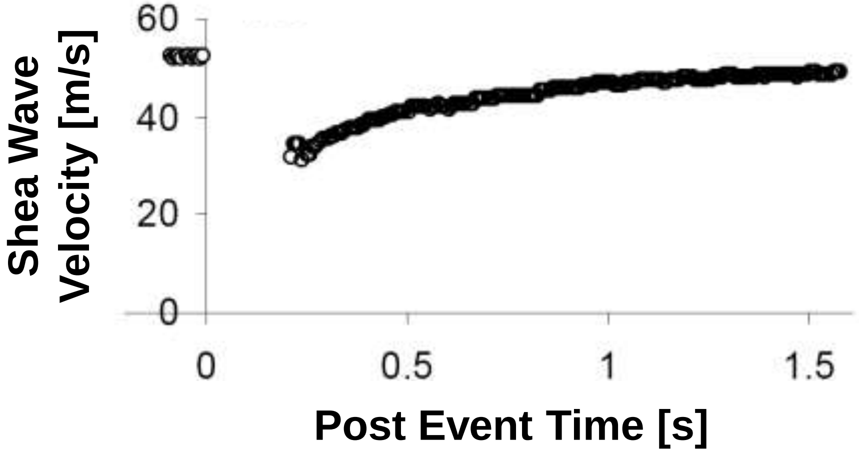
V. Rinaldi

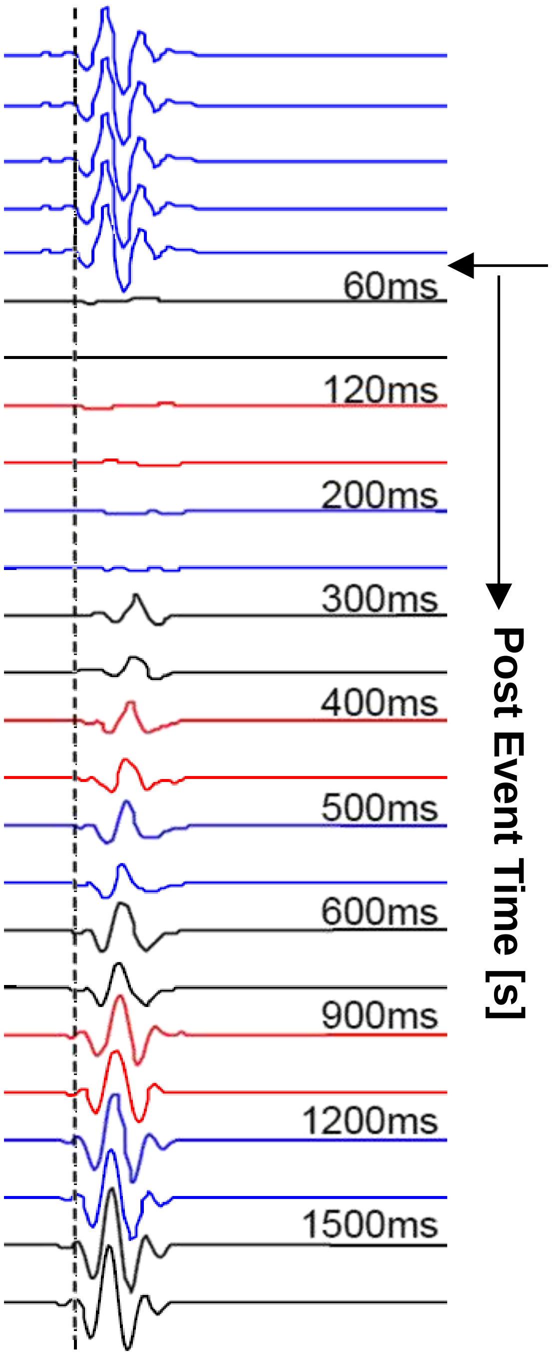
Laboratory Testing



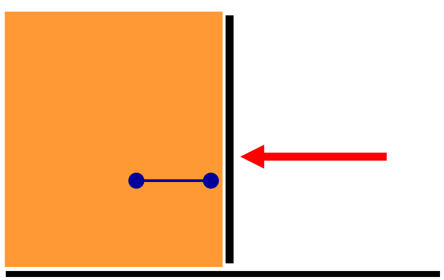
S-monitoring: Liquefaction

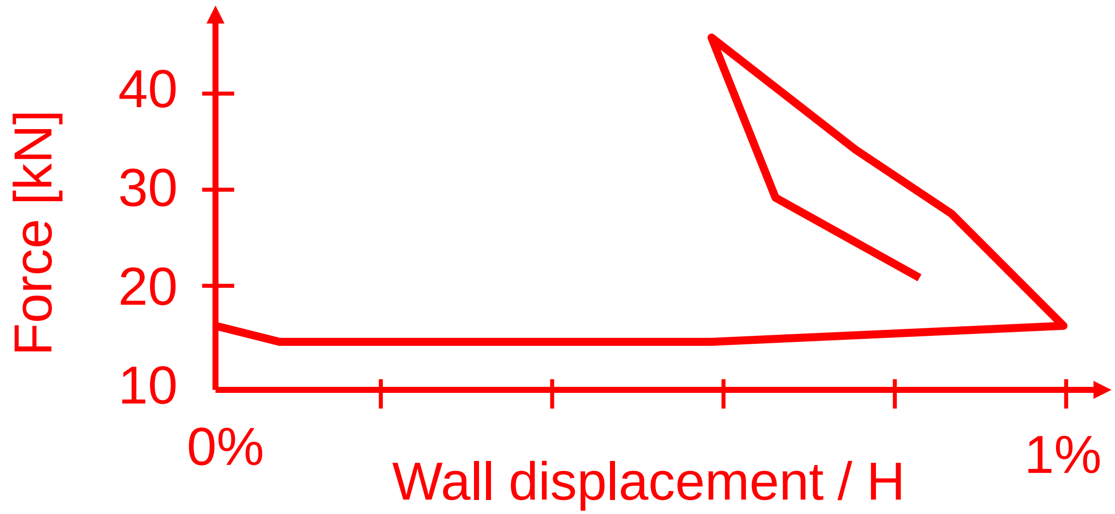


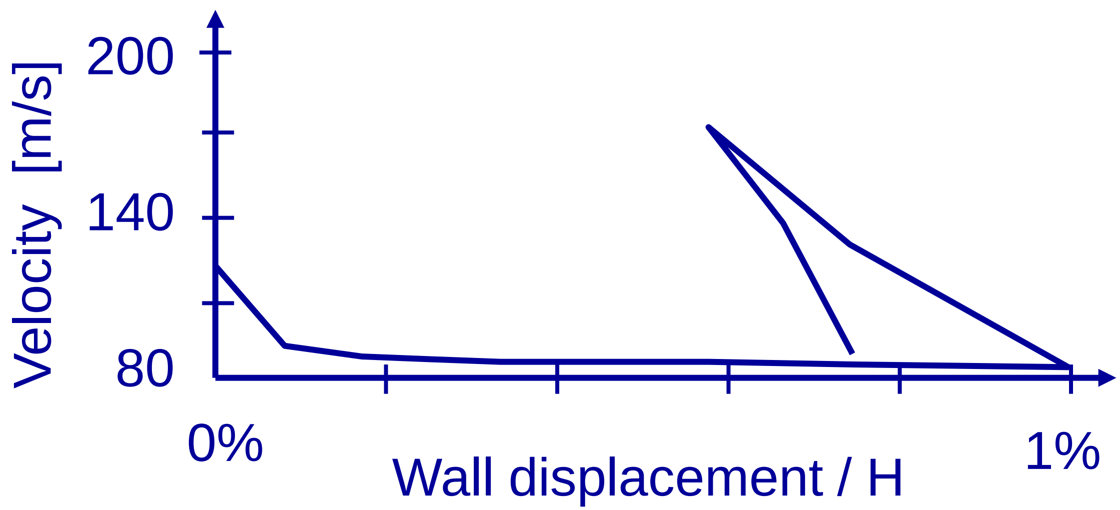




S-monitoring: Excavation & Retaining Walls

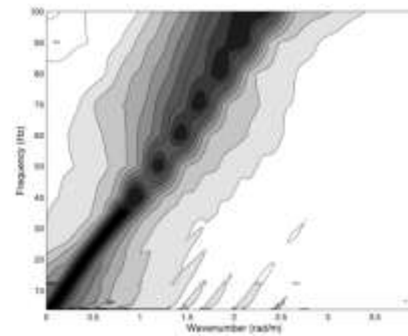
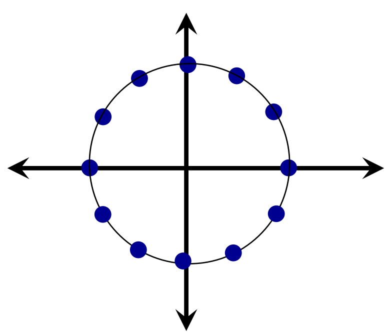
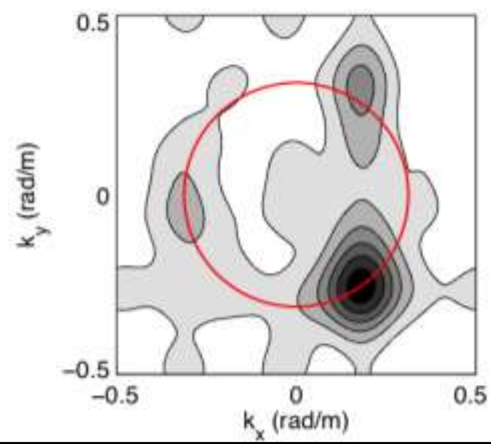






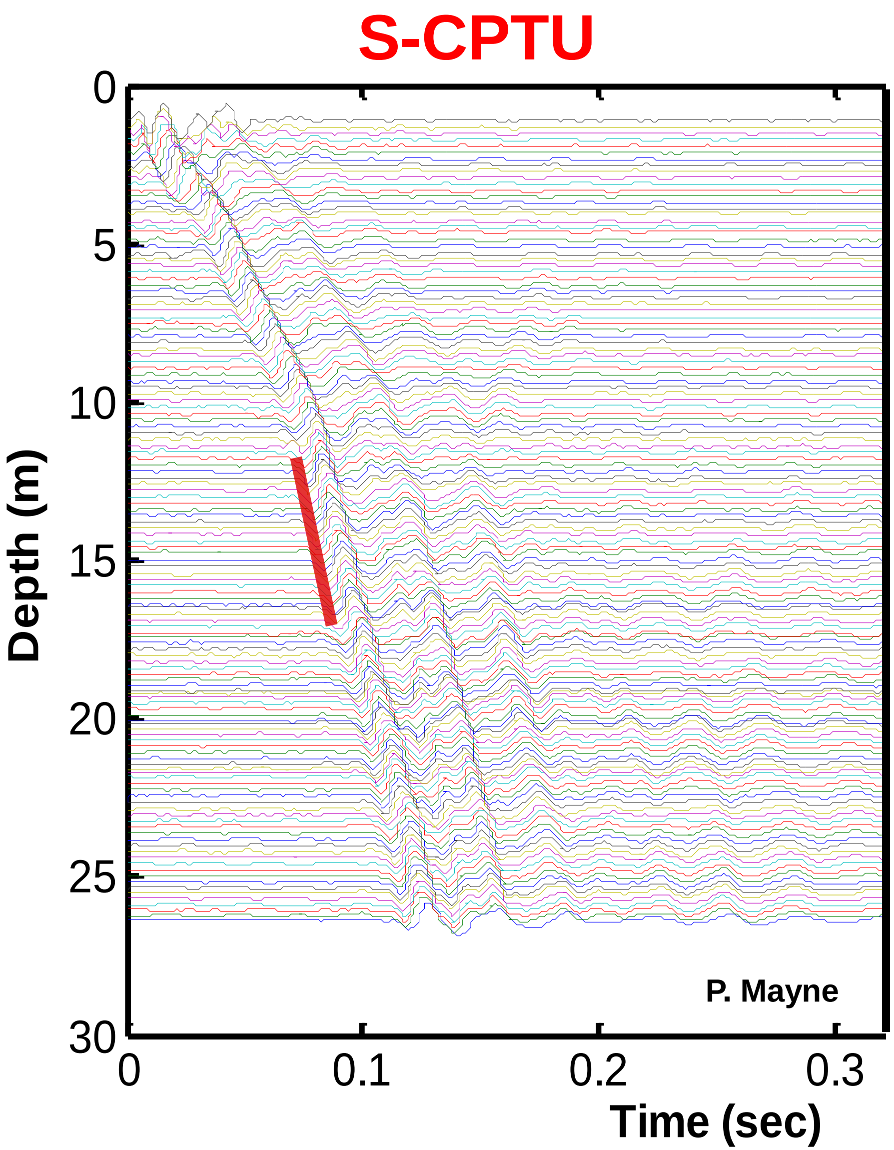
Field: Surface Waves
(*non-invasive*)

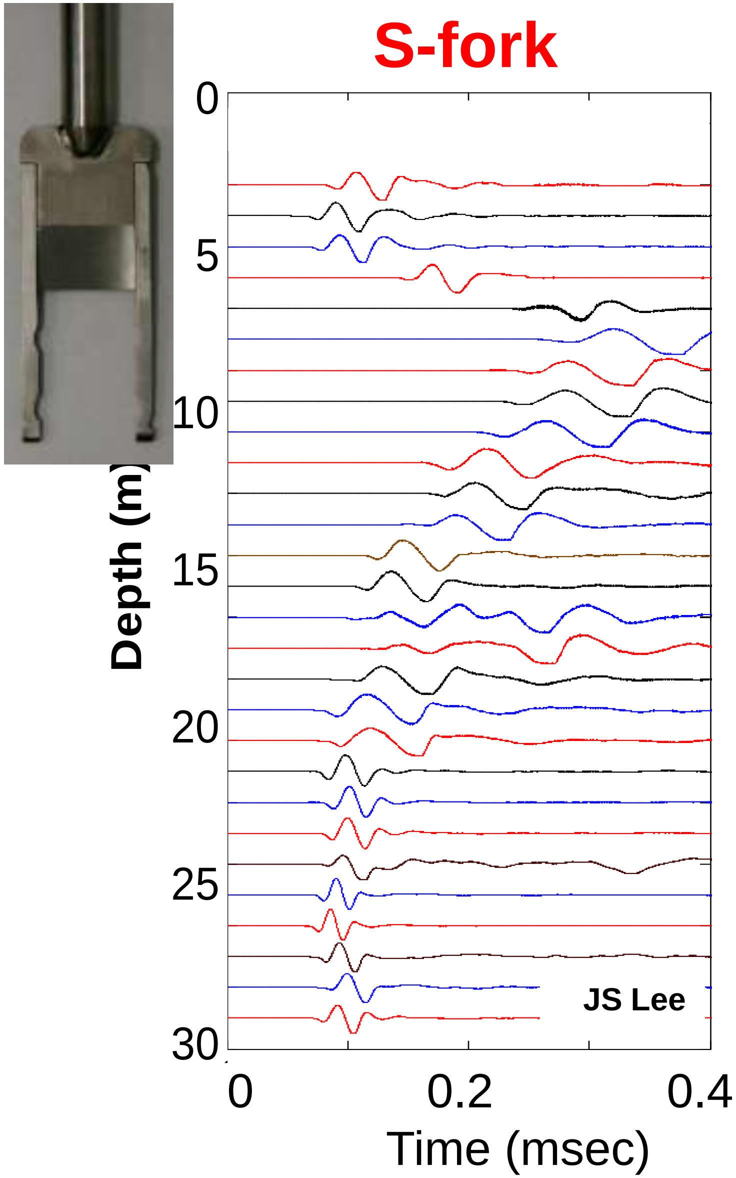
Sensor Arrays

Active		
Pasive		

G. Rix

Field: Penetration-based (*invasive*)





Mechanical Waves

attenuation

S-waves

P-waves

$$V_P = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{B + \frac{4}{3}G}{\rho}}$$

Bulk Stiffness

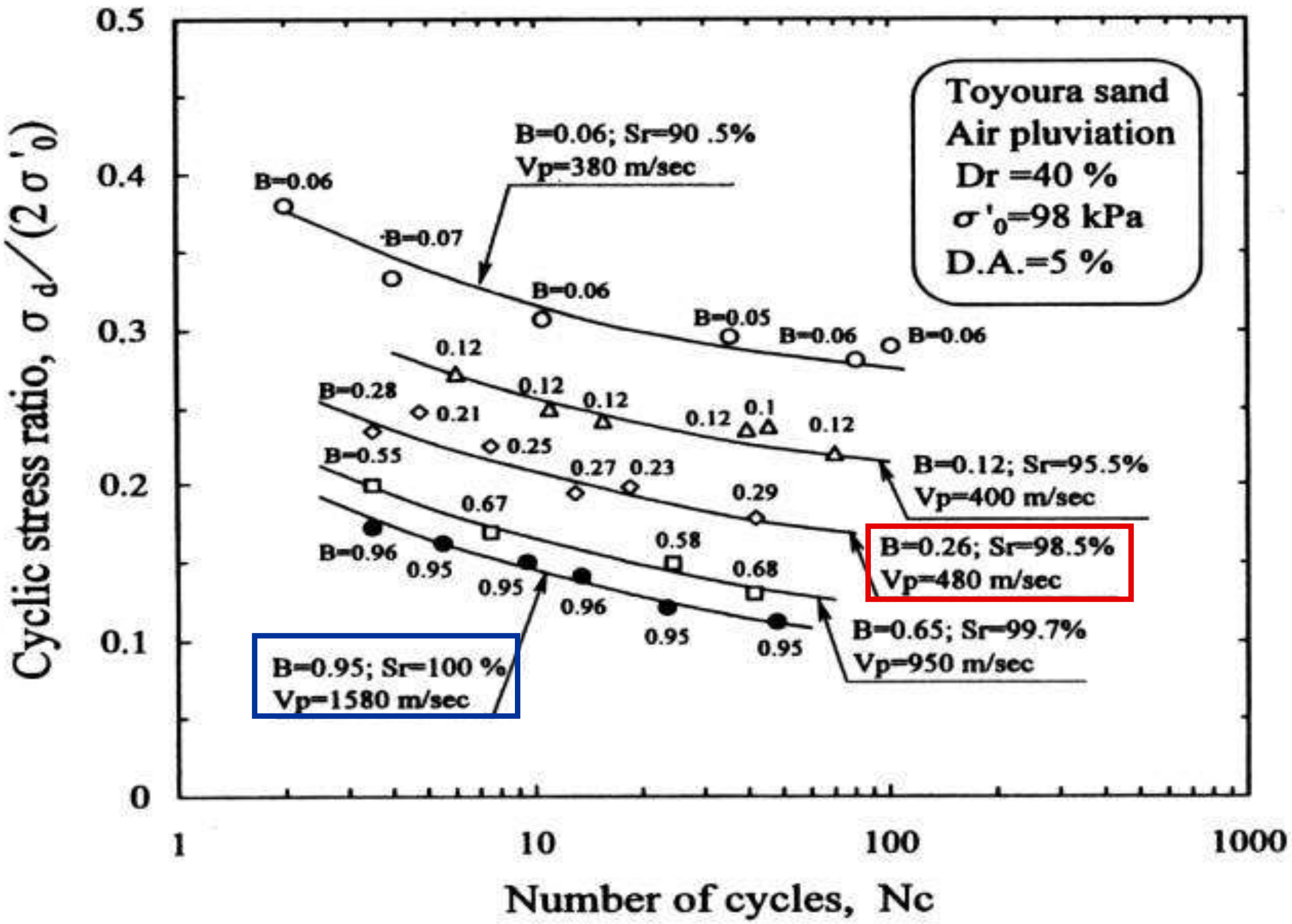
$$V_P = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{B + \frac{4}{3}G}{\rho}}$$

Fluid Mixture	$B_{fl} = \left(\frac{S_r}{B_w} + \frac{1-S_r}{B_a} \right)^{-1}$	$\rho_{fl} = (1-S_r)\rho_a + S_r\rho_w$
Suspension	$B_{sus} = \left(\frac{1-n}{B_g} + \frac{n}{B_{fl}} \right)^{-1}$	$\rho_{sus} = (1-n)\rho_g + n\rho_{fl}$
Soil (fluid + skeleton)	$B_{soil} = B_{sus} + B_{sk}$	$\rho_{soil} = \rho_{sus} = (1-n)\rho_g + n\rho_{fl}$

from $G = V_s^2 \rho$

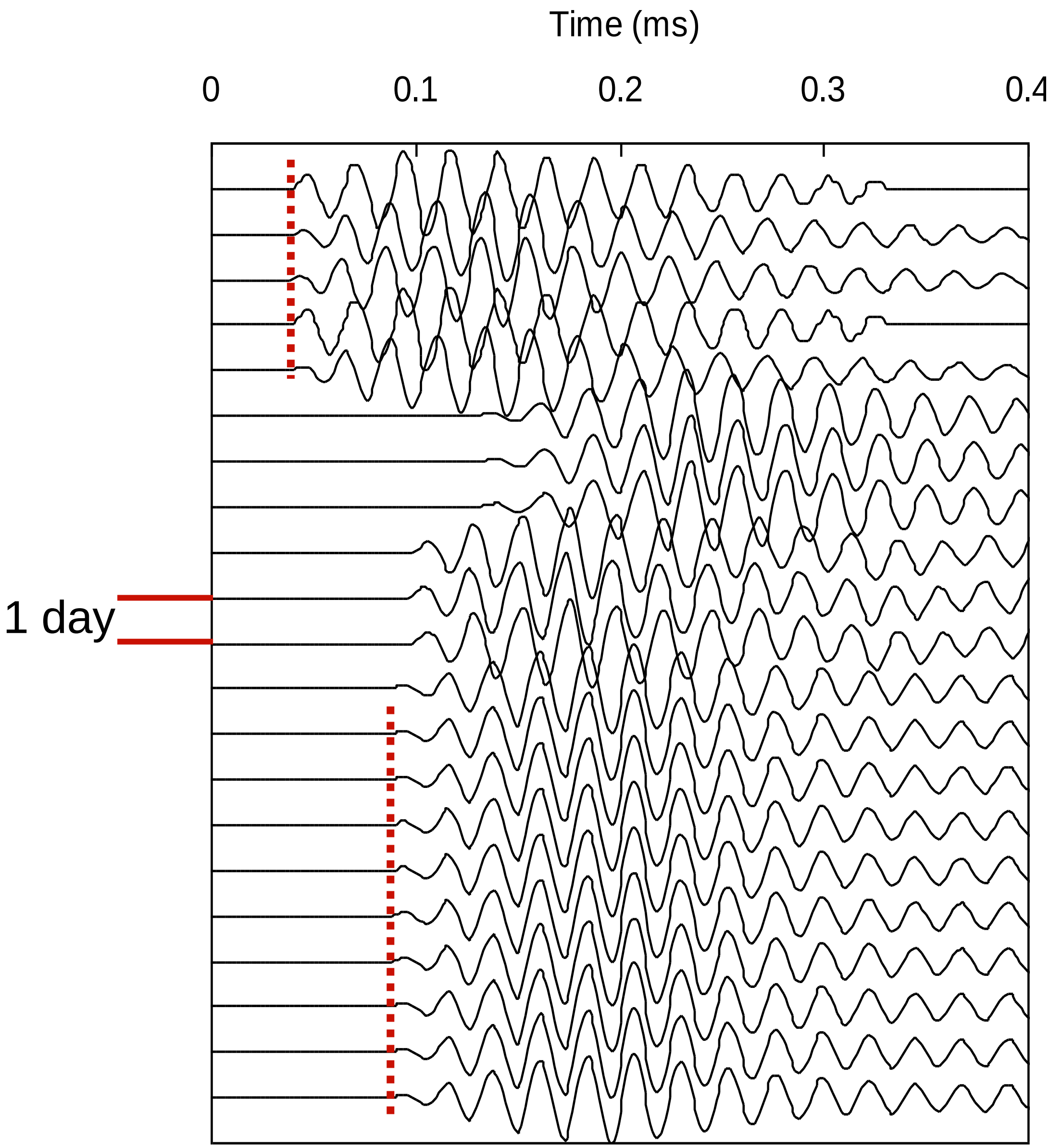
Saturation

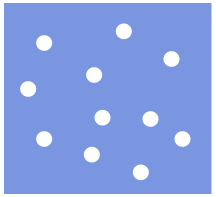
$$V_P = \sqrt{\frac{\left(B_{sk} + \frac{4}{3}G_{sk}\right) + \left[n\left(\frac{S}{B_w} + \frac{1-S}{B_a}\right) + \frac{1-n}{B_g}\right]^{-1}}{(1-n)\rho_g + nS\rho_w}}$$



K. Ishihara

P-monitoring: Bio-gas





Paracoccus denitrificans
Nitrate broth
F110 + 3%Kaolin

V. Rebata

V_P and V_S

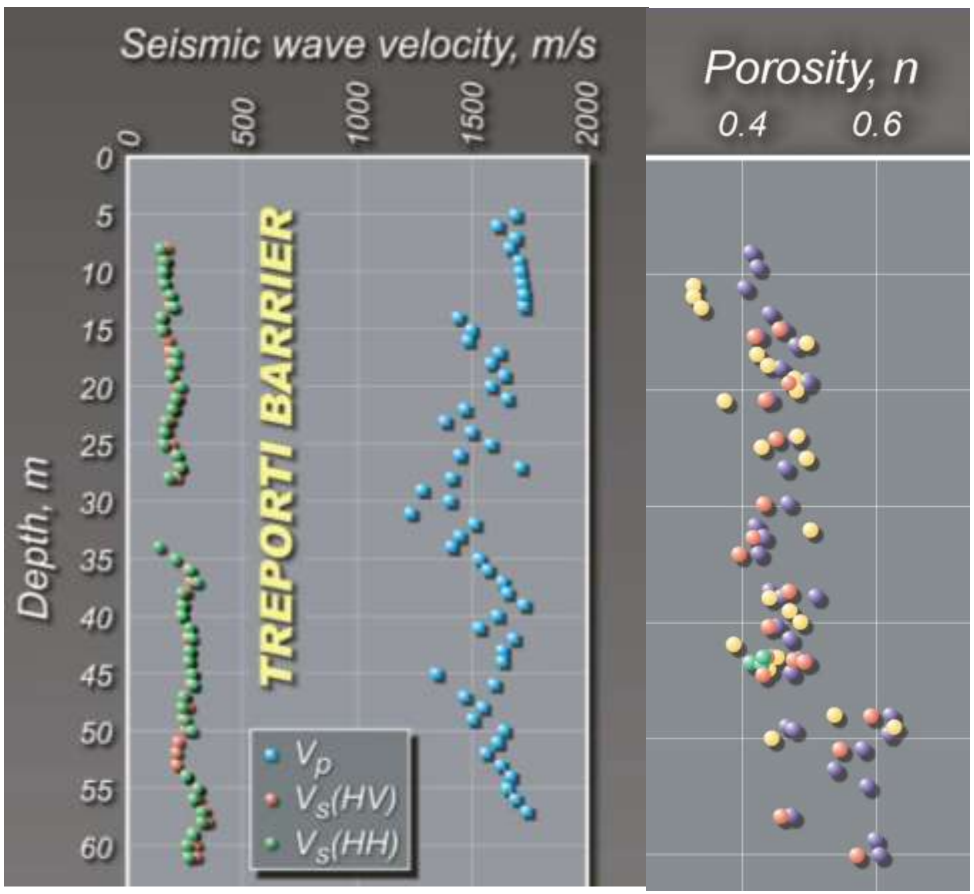
Poisson's ratio (~dry)

$$\nu = \frac{\frac{1}{2}\left(\frac{V_P}{V_S}\right)^2 - 1}{\left(\frac{V_P}{V_S}\right)^2 - 1}$$

Porosity (S=100%)

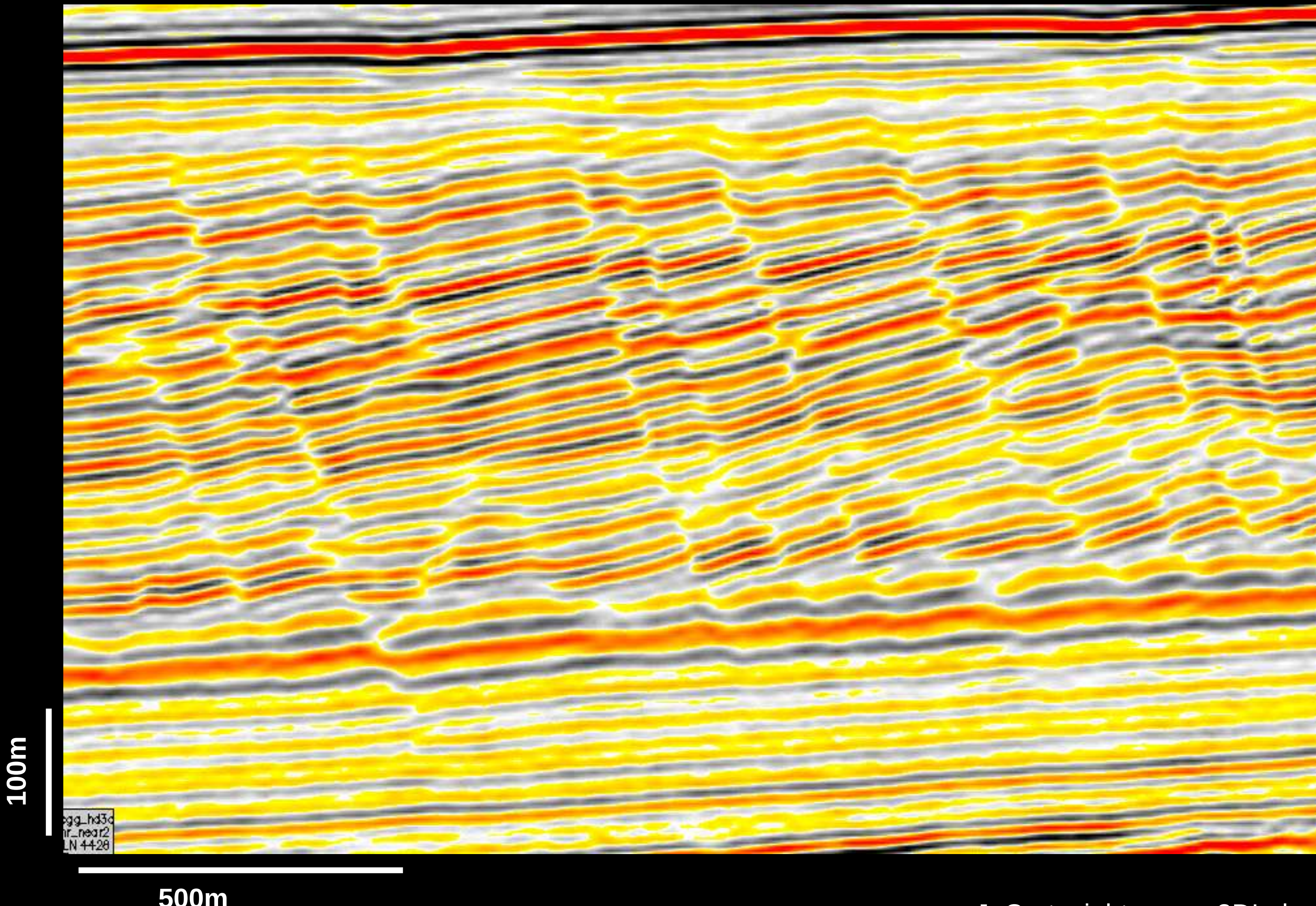
$$n = \frac{\rho_g - \sqrt{\rho_g^2 - \frac{4\left(\rho_g - \rho_{fl}\right)B_{fl}}{V_P^2 - 2\left(\frac{1-\nu_{sk}}{1-2\nu_{sk}}\right)V_S^2}}}{2\left(\rho_g - \rho_{fl}\right)}$$

see Foti & Lancelotta

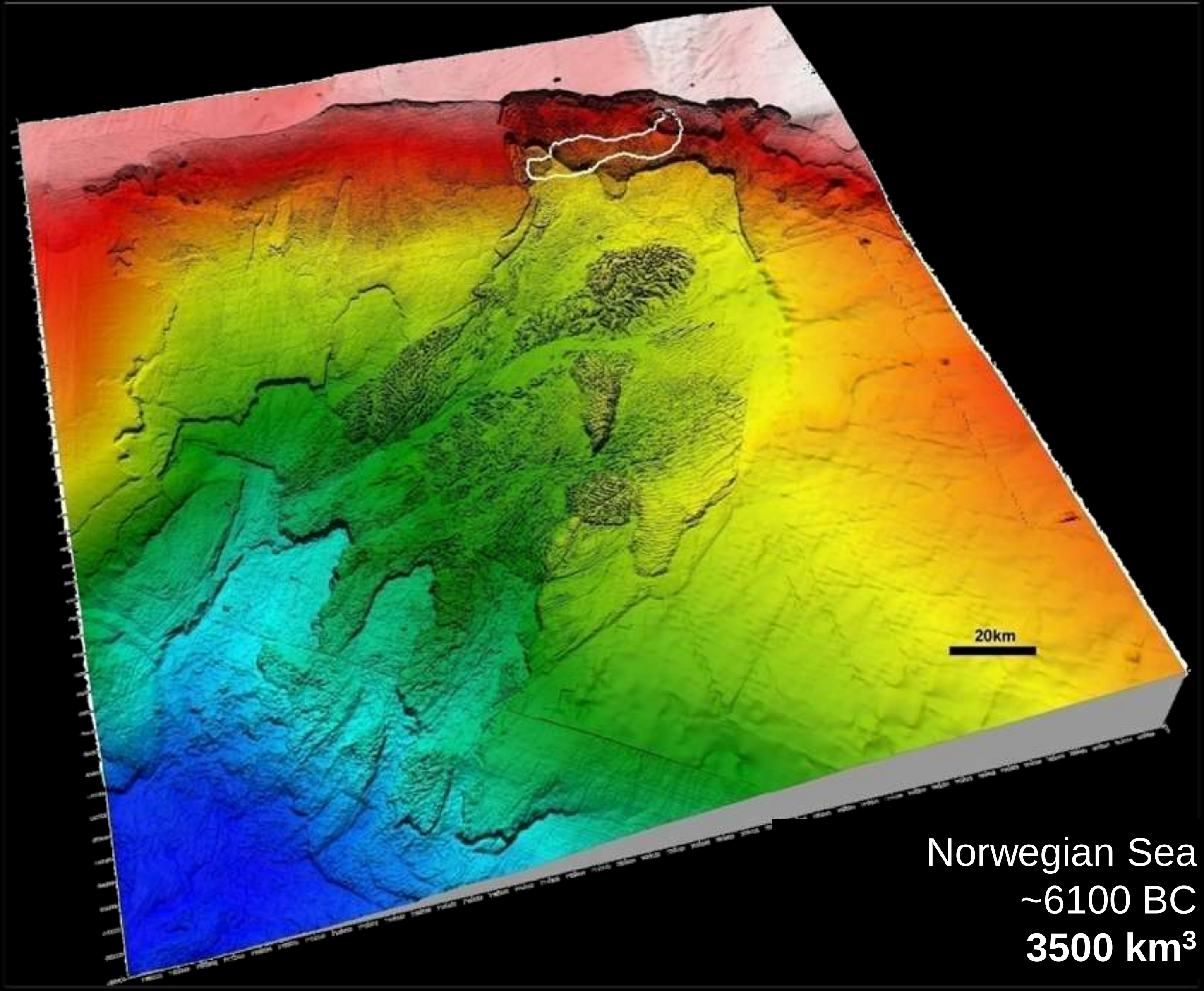


Venice (M. Jamiolkowski)

New Phenomena: Polygonal Faults



Massive Landslide - Storegga



Norwegian Sea
~6100 BC
3500 km^3

J. Cartwright - www.3DLab.org.uk

Summary: P- and S-waves

Waves	Small-strain phenomena
	May be used to monitor large-strain processes
V_s	Skeletal stiffness: G ➔ Geo-mechanical design
	Effective stress, suction, cementation
	Sampling: pronounced effect ➔ measure in situ !
	Simple lab & field devices and methods
V_P	Fluid & skeletal stiffness: B & G
	Proximity to full saturation
V_P & V_s:	Dry ➔ skeletal Poisson's ratio
	Saturated ➔ porosity
	Spatial variability

Mechanical Waves

Electromagnetic Waves

μ

ε

σ_{el}

Thermal Phenomena

Processing

Maxwell's Equations

and God said:

Gauss - E	$\frac{q}{\varepsilon_o} = \oint_S \bar{E} \cdot \bar{ds}$	$\nabla \cdot \bar{E} = \frac{\rho_v}{\varepsilon_o}$
Gauss - B	$\oint_S \bar{B} \cdot \bar{ds} = 0$	$\nabla \cdot \bar{B} = 0$
Faraday	$\oint_\ell \bar{E} \cdot \bar{d\ell} = -\frac{d\phi_B}{dt}$	$\nabla \times \bar{E} = -\frac{d\bar{B}}{dt}$
Ampere-Maxwell	$\oint_\ell \bar{B} \cdot \bar{d\ell} = \mu_o \varepsilon_o \frac{d\phi_E}{dt} + \mu_o i$	$\nabla \times \bar{H} = \mu_o \left(\varepsilon_o \frac{d\bar{E}}{dt} + \sigma \bar{E} \right)$

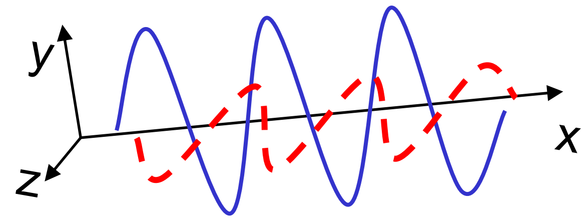
and there was light…

Wave equation

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

Maxwell's Equations – Wave Propagation

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



Conductivity σ_{el} *all forms of losses*

Permittivity $\kappa = \varepsilon/\varepsilon_o$

Permeability μ *non-ferromagnetic μ=1* *ferromagnetic*

Electromagnetic Wave Propagation

Velocity

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

Skin Depth

$$S_{d} = \frac{1}{\mathrm{Re}\left(\sqrt{j\omega\sigma\mu^{*} - \omega^{2}\varepsilon^{*}\mu^{*}}\right)}$$

non-ferromagnetic

Electromagnetic Wave Propagation

Velocity

$$V = c_0 \frac{1}{\sqrt{\frac{1}{2}\left[\sqrt{\kappa^2 + \left(\frac{\sigma}{\varepsilon_o \omega}\right)^2} + \kappa\right]}}$$

Skin Depth

$$S_d = \frac{c_0}{\omega} \frac{1}{\sqrt{\frac{1}{2}\left[\sqrt{\kappa^2 + \left(\frac{\sigma}{\varepsilon_o \omega}\right)^2} - \kappa\right]}}$$

Electromagnetic Properties

→ *permeability*

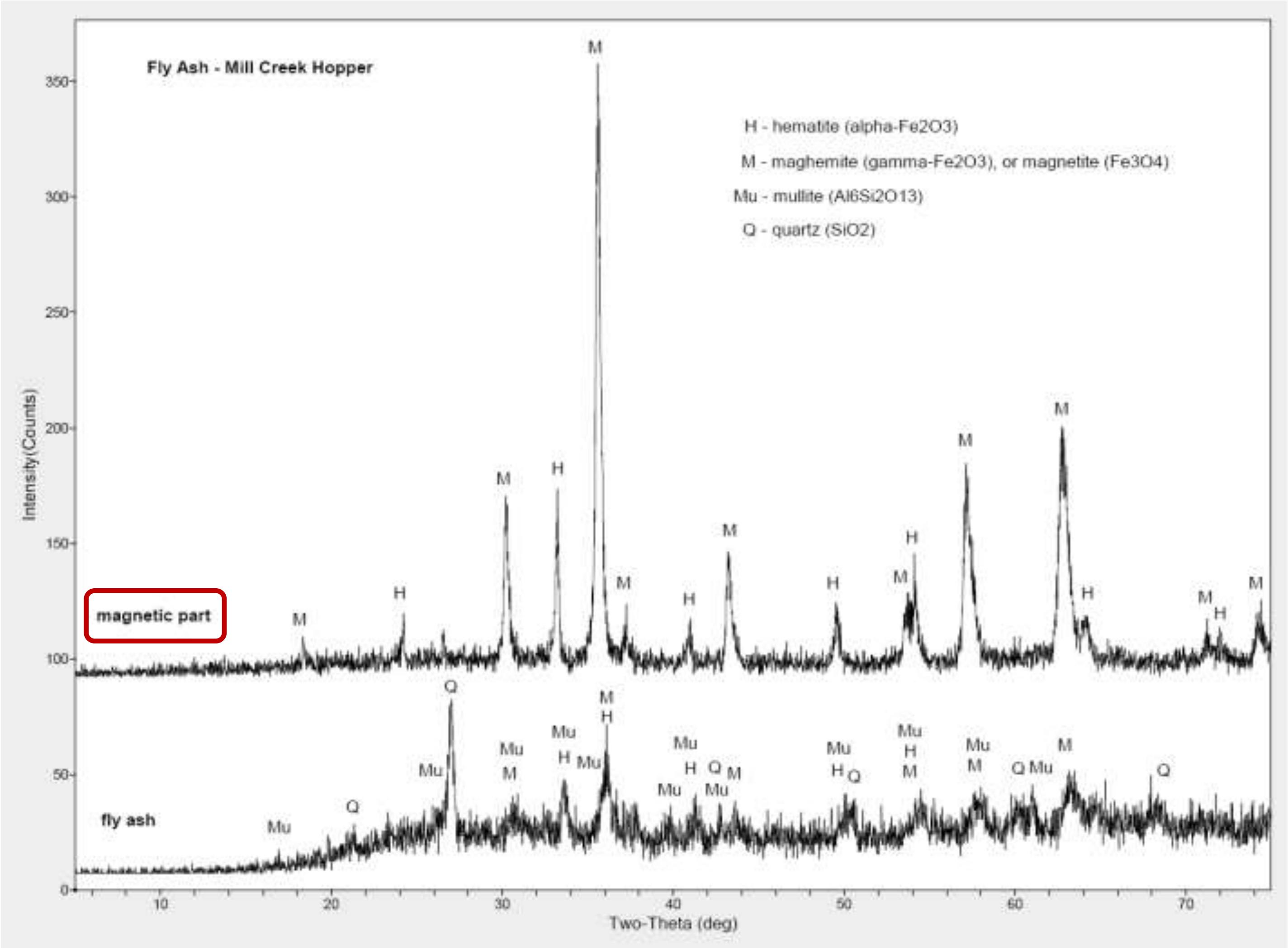
conductivity

permittivity

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).

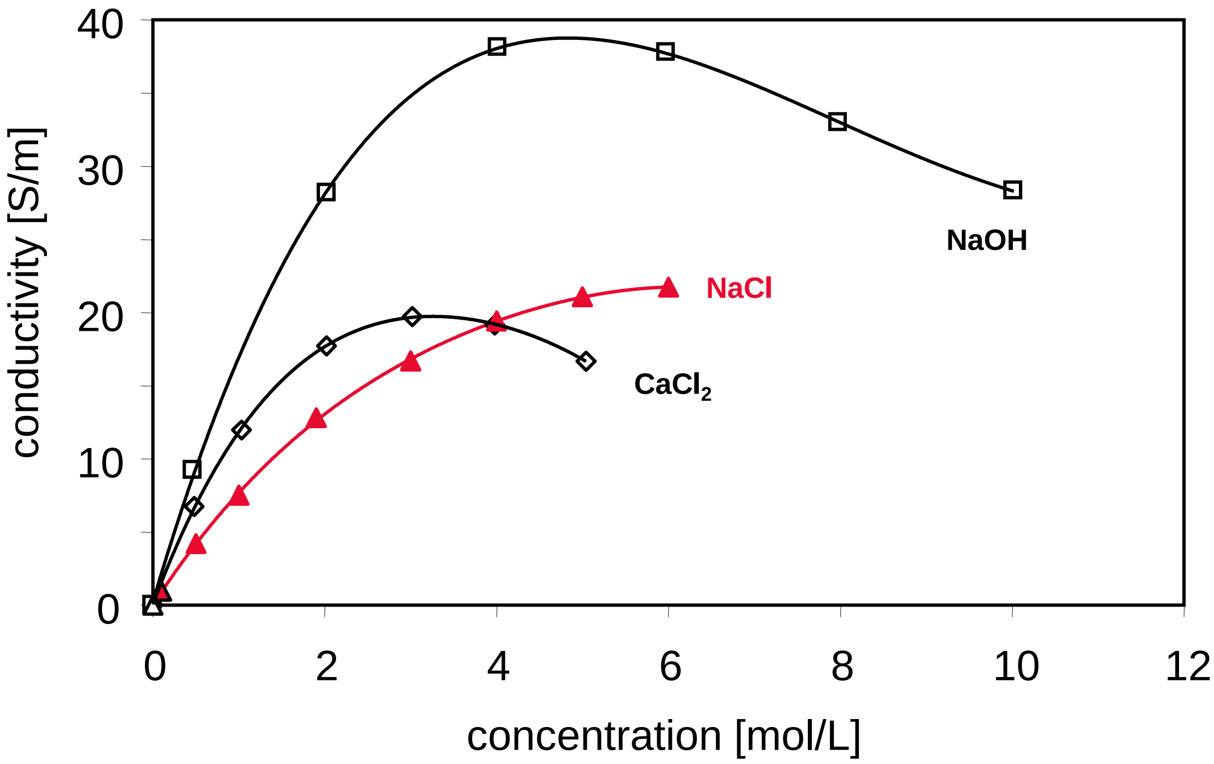
Electromagnetic Properties

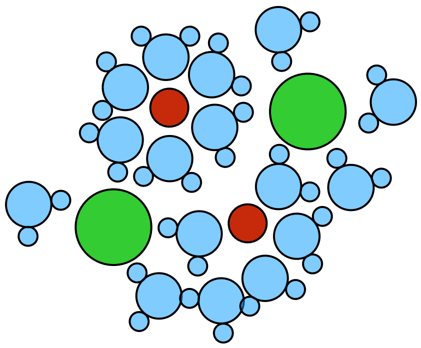
permeability

→ *conductivity*

permittivity

Electrical Conductivity of the Pore Fluid



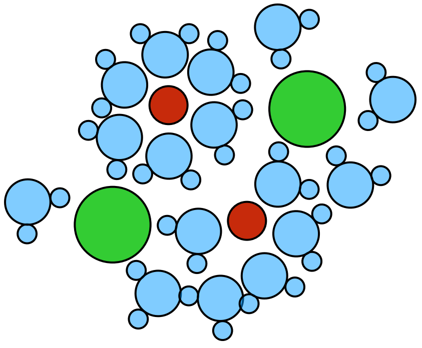


At low concentration (P. Annan):

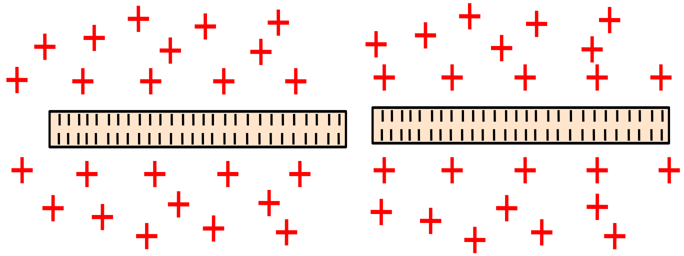
$$\sigma_{fl}\,[mS/m] = 0.15 \cdot TDS\,[mg/L]$$

Electrical Conductivity of Soils

Pore fluid (pores)



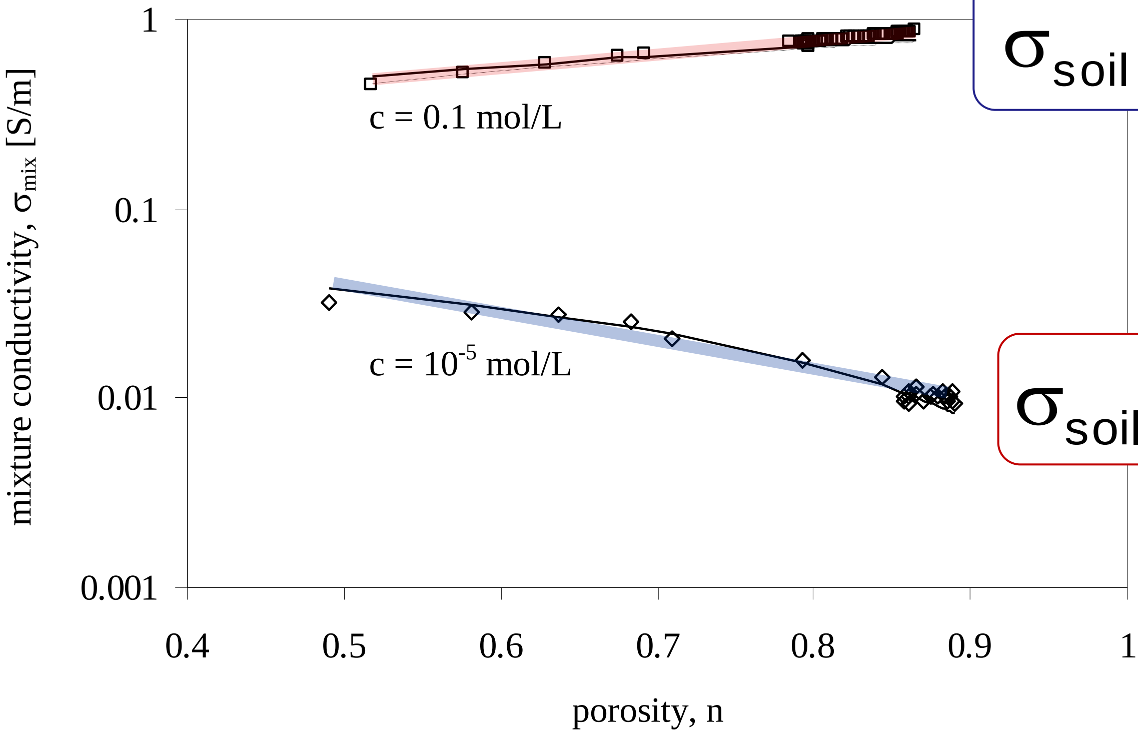
Surface conduction



Wet Soil

$$\sigma_{soil} = n\sigma_{fl}$$

Electrical Conductivity of Soils

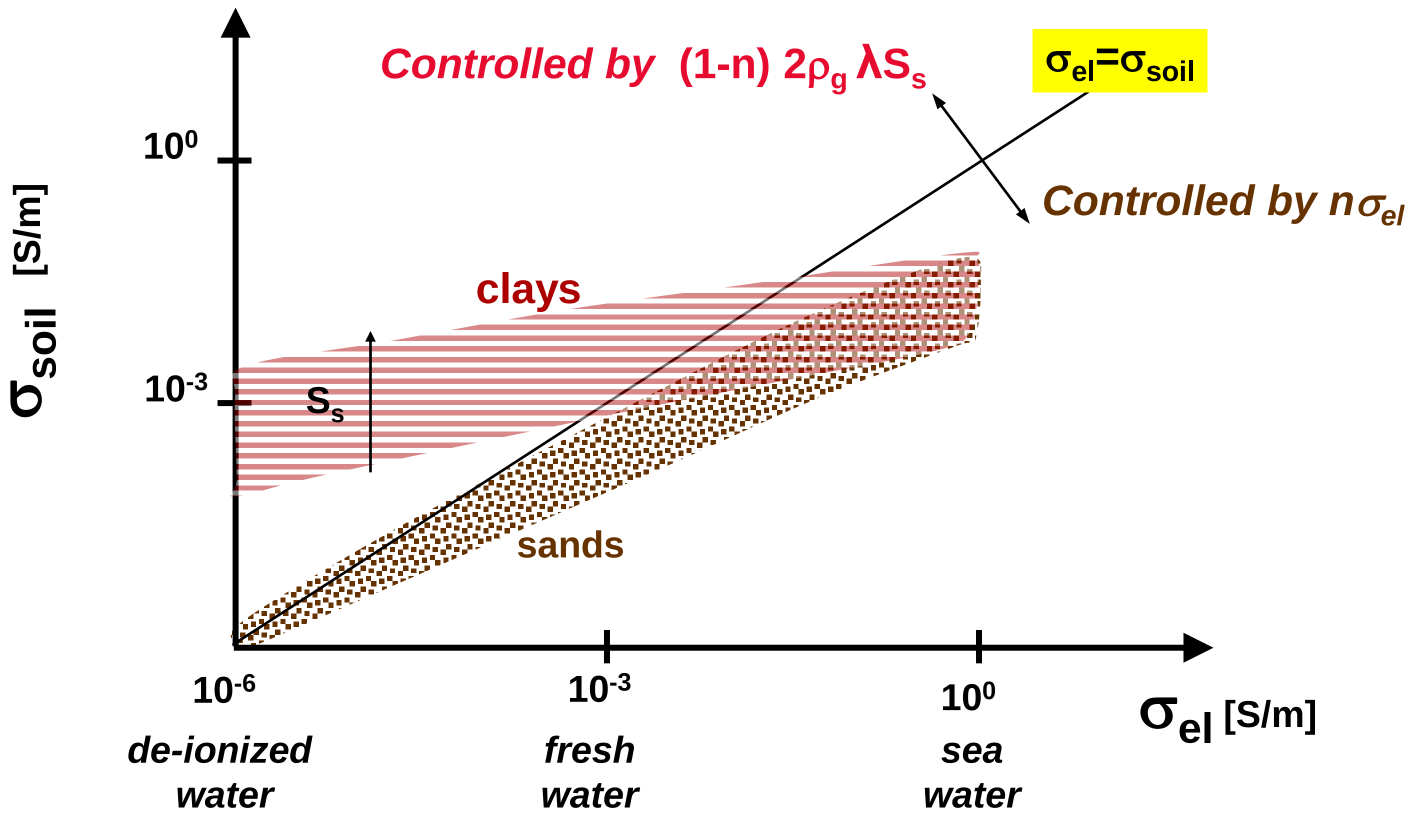


$$\sigma_{soil} = n^{\beta}\sigma_{fl}$$

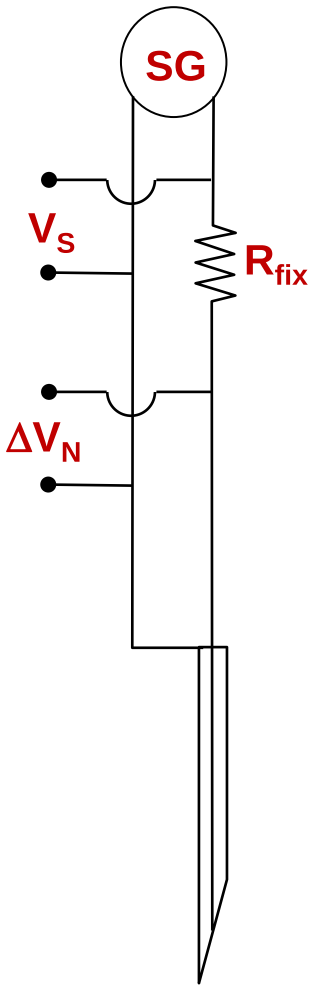
Archie

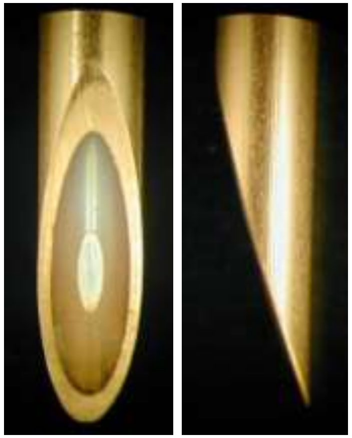
$$\sigma_{soil} = n\sigma_{fl} + (1-n)\alpha S_s$$

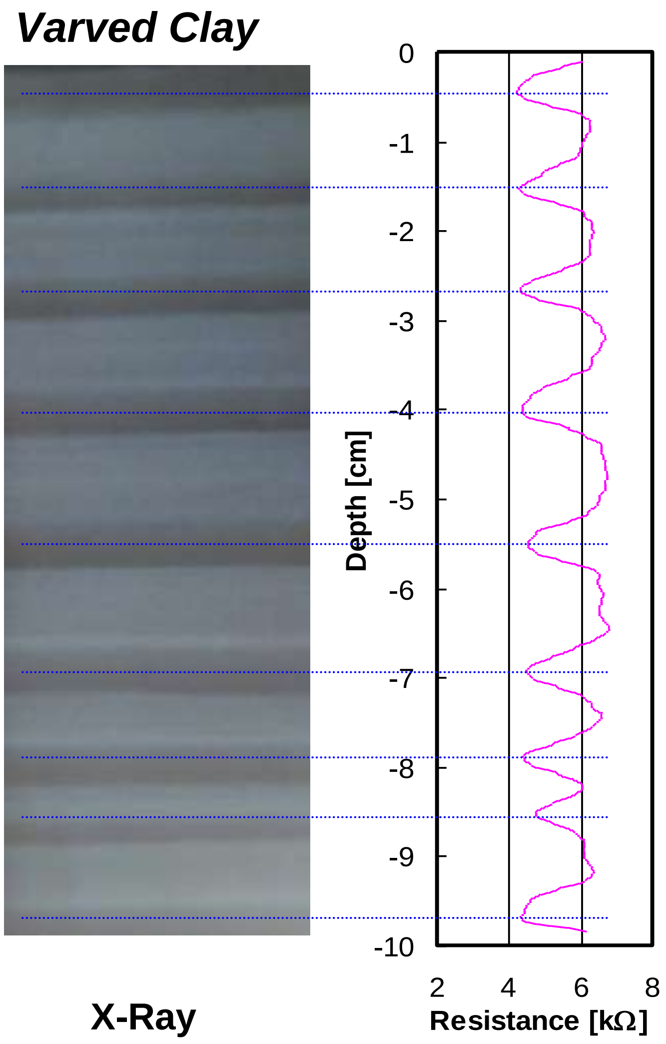
Summary: Electrical Conductivity



Laboratory: Electrical Needle







Electromagnetic Properties

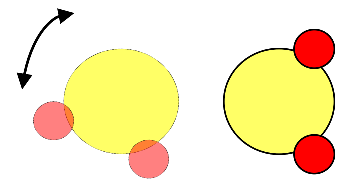
permeability

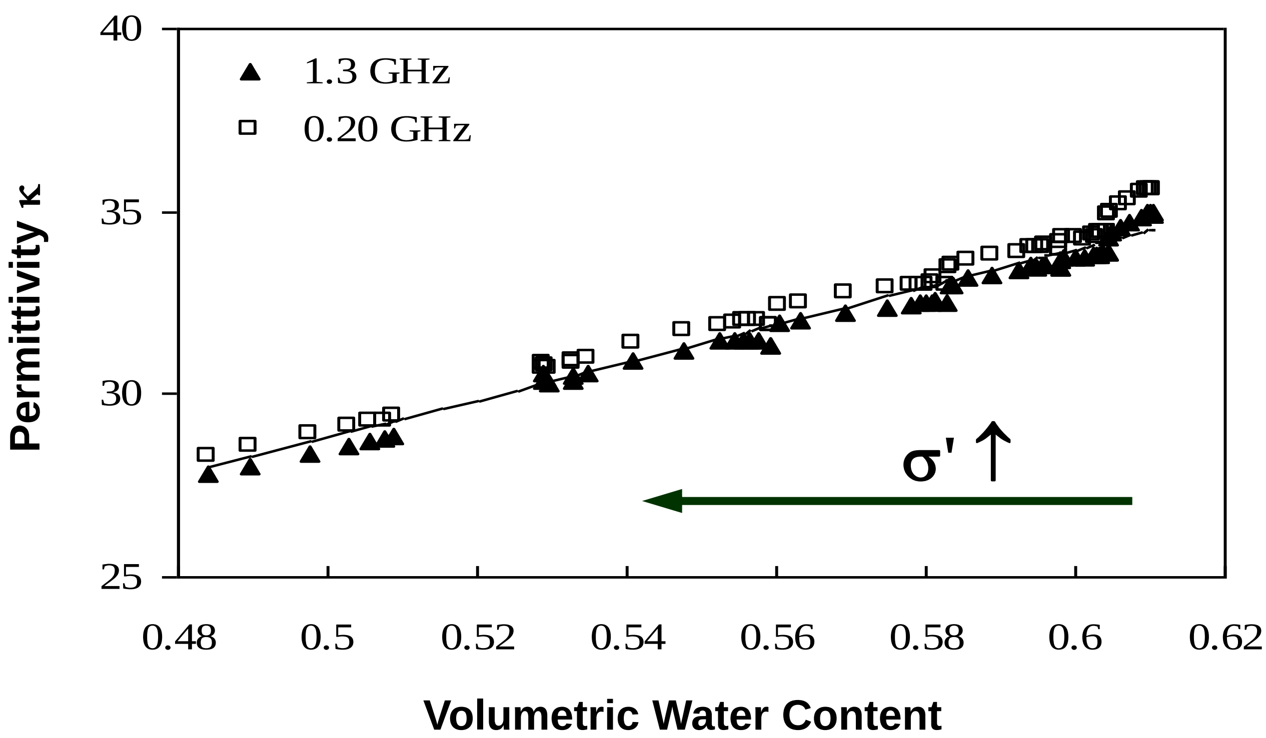
conductivity

→ *permittivity*

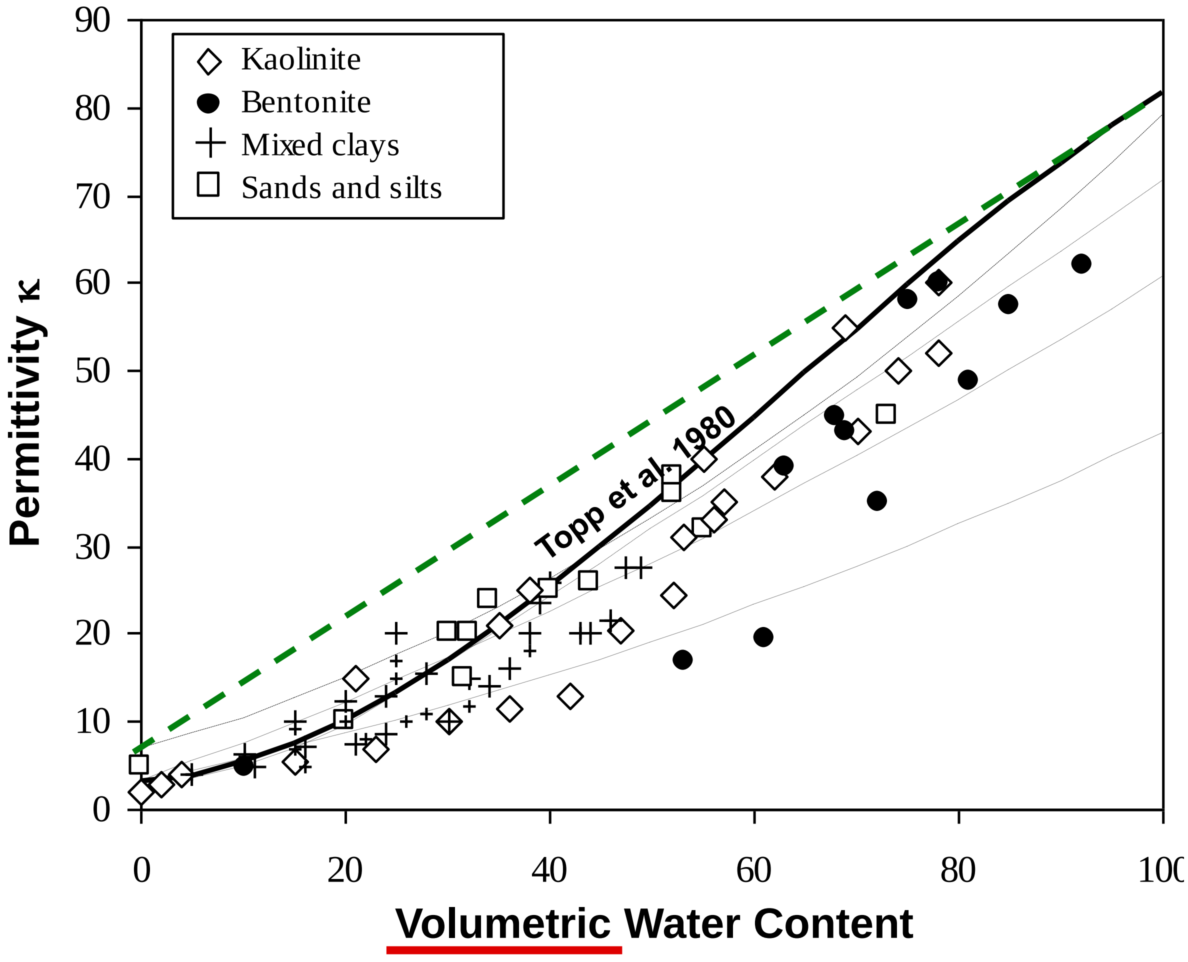
Free Water - Consolidation

Orientational Pol.





Permittivity of Wet Soils



Summary: Relative Permittivity

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

$$\kappa'_{soil} < (1-n)\kappa'_{\mathrm{m}} + n(1-S) + nS\kappa'_{w}$$

Linear mixture

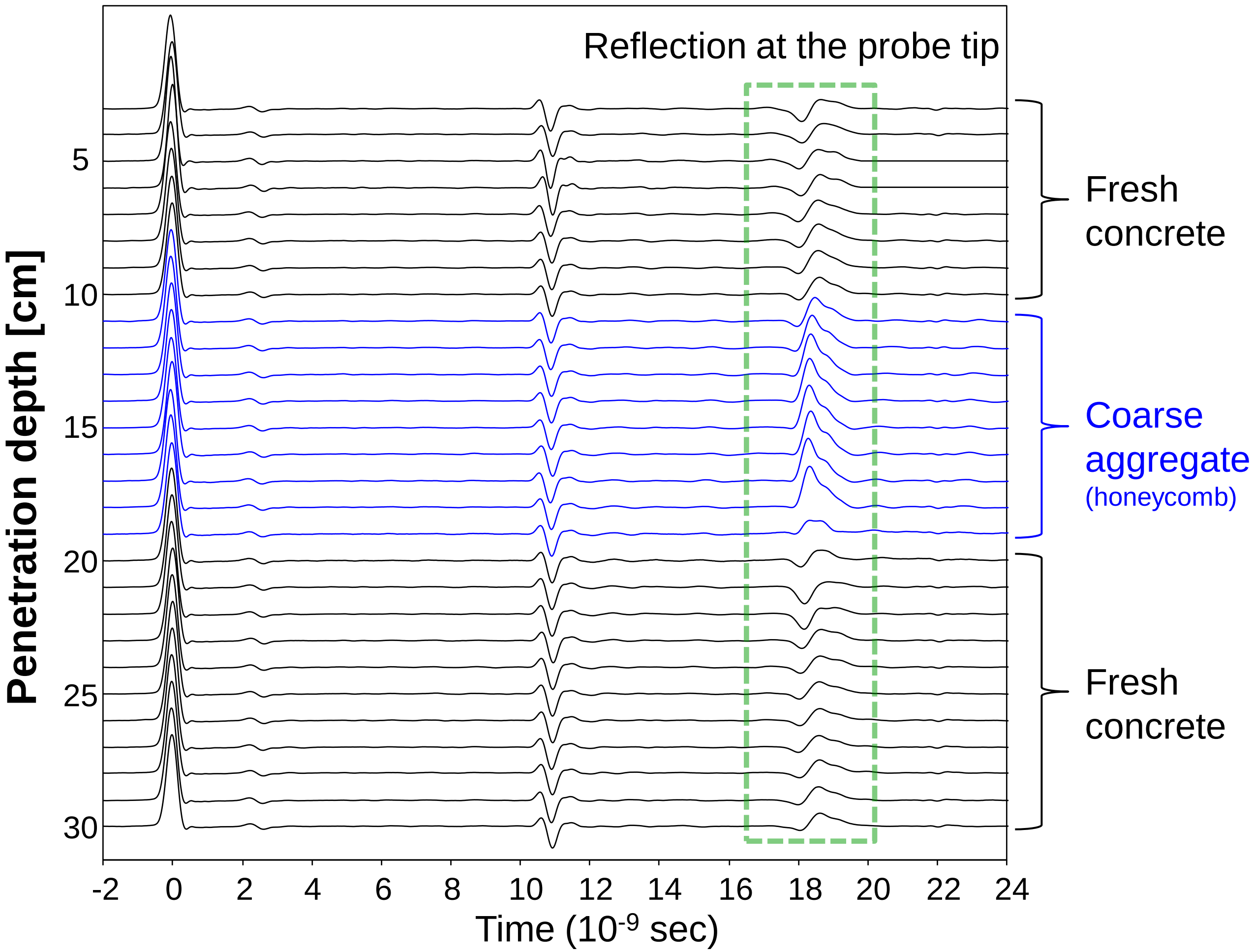
$$\kappa'_{soil} = \left[(1-n)\sqrt{\kappa'_{m}} + n(1-S) + nS\sqrt{\kappa'_{w}}\right]^2$$

CRIM

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

Topp et al. 1980

TDR Probe – Honeycombs

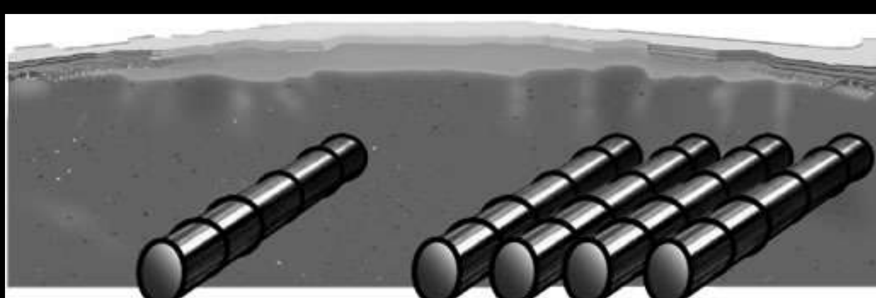


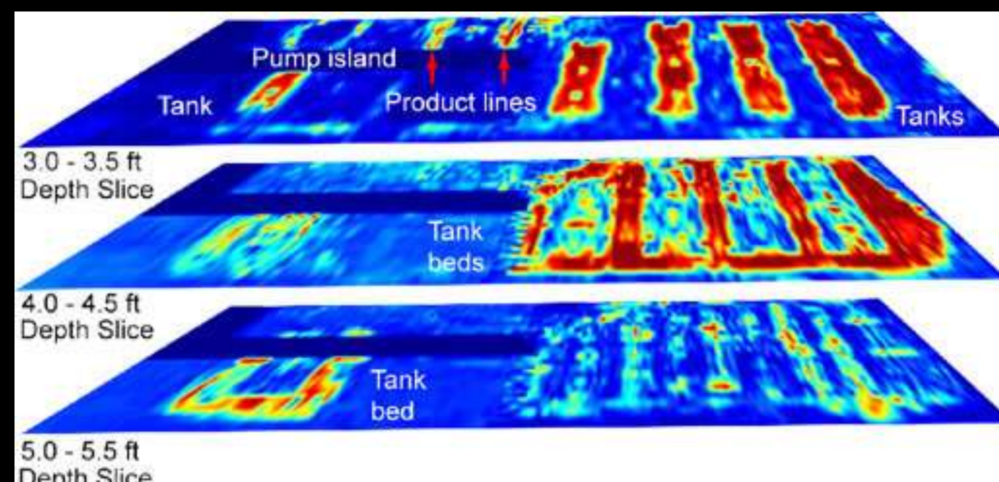
Cone in TDR-mode

MS Cha

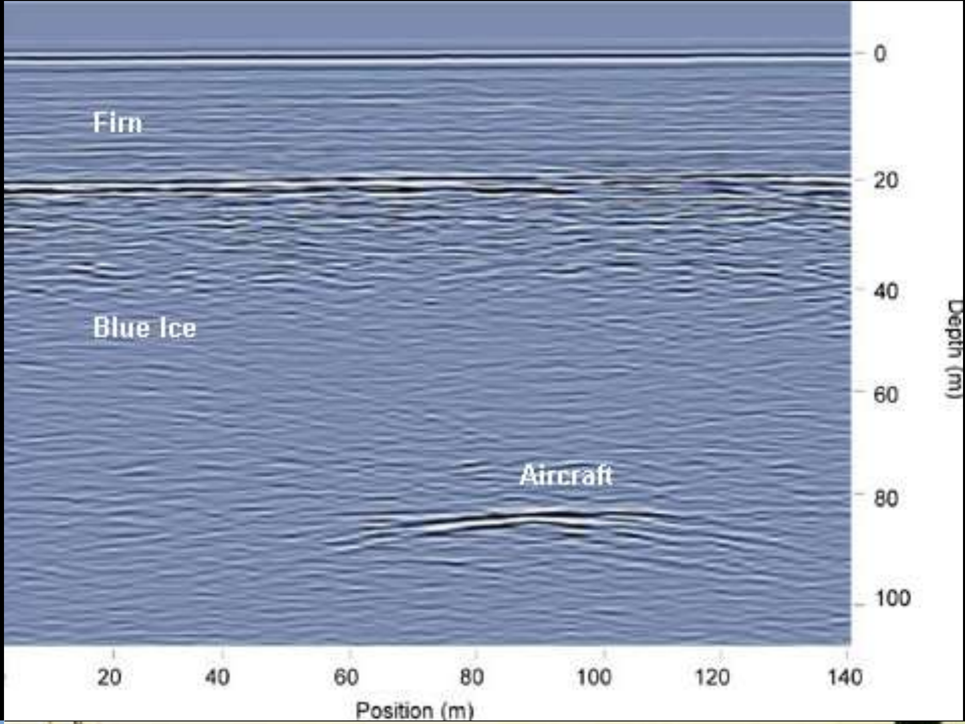
GPR - 2D & 3D


Tank
Tanks
Tank beds



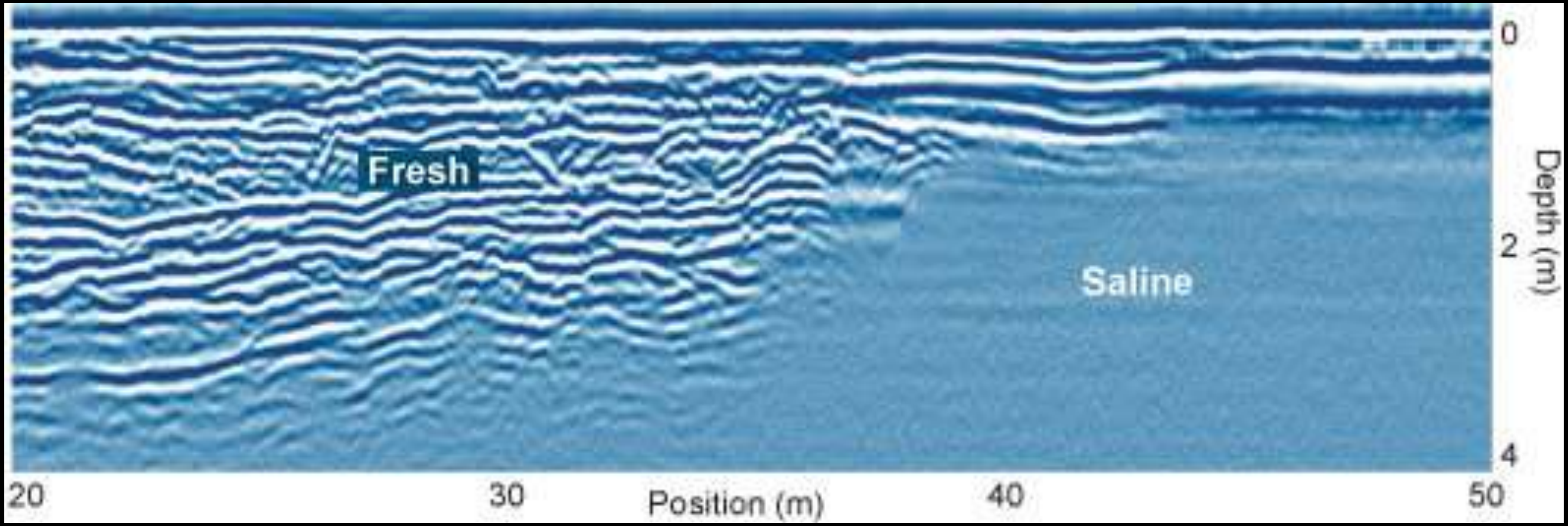

Pump island
Tank
Product lines
Tanks
3.0 - 3.5 ft
Depth Slice
Tank
beds
4.0 - 4.5 ft
Depth Slice
Tank
bed
5.0 - 5.5 ft
Depth Slice

GPR on Ice



www.sensoft.ca

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 *(invasive)***	
κ	**free water orientation (microwave frequency)** **GPR TDR probe *(invasive)***	
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**

Mechanical Waves

Electromagnetic Waves

Thermal Phenomena

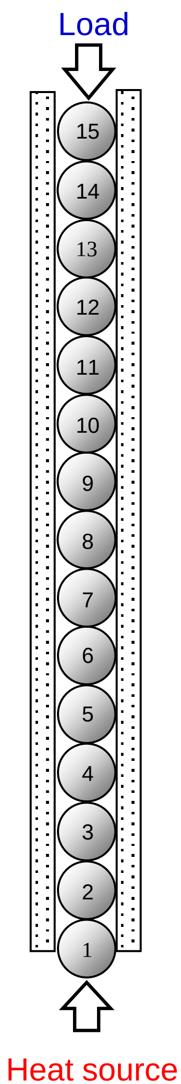
L

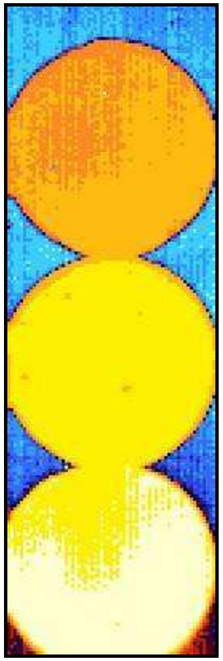
c_p

k_T

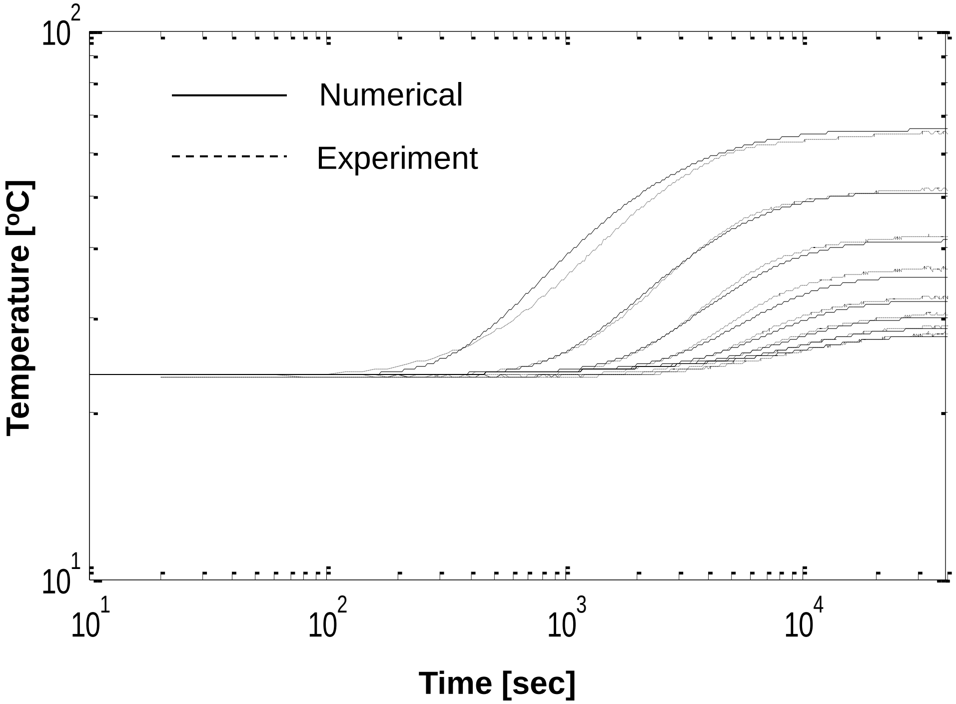
Processing

Particle-level Experiments



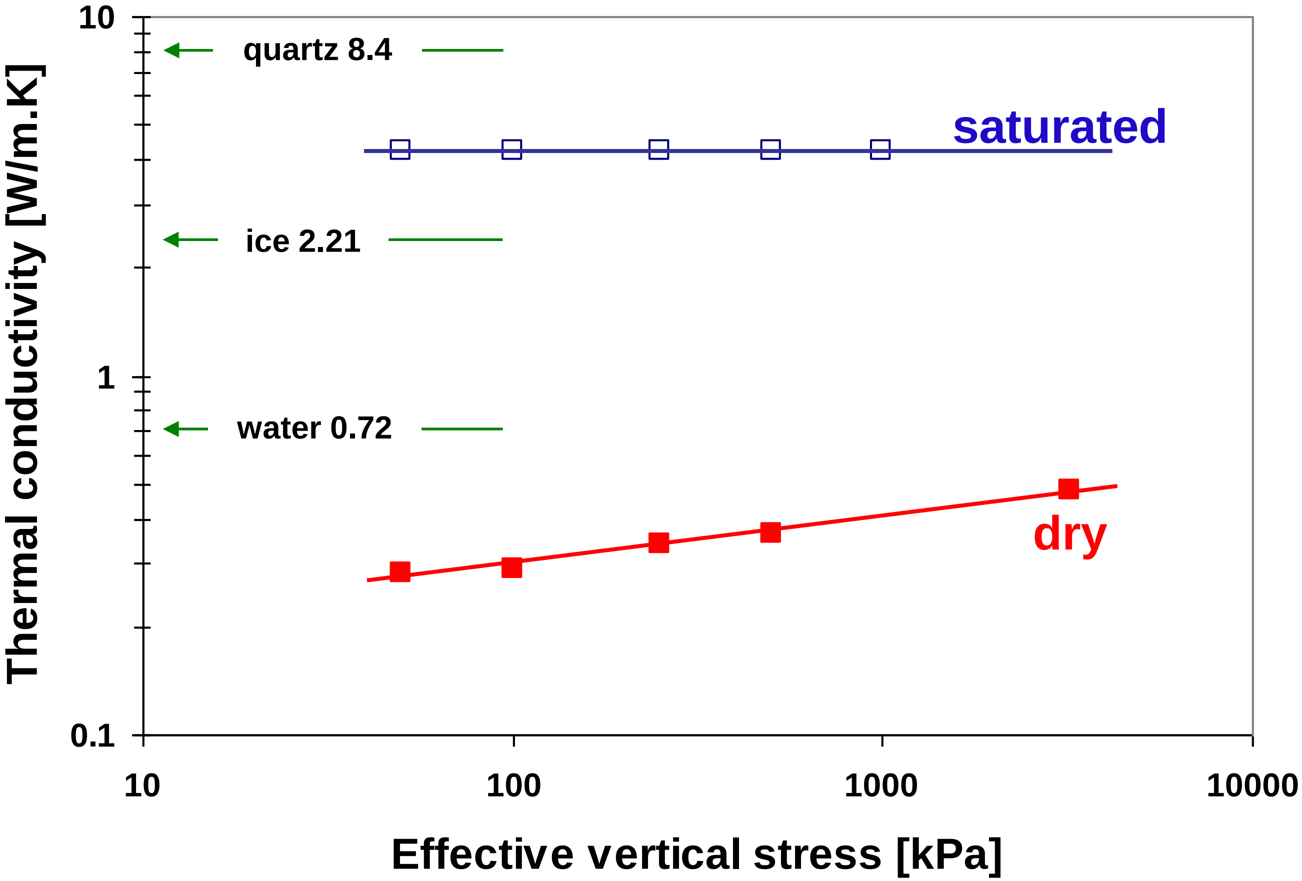


TS Yun



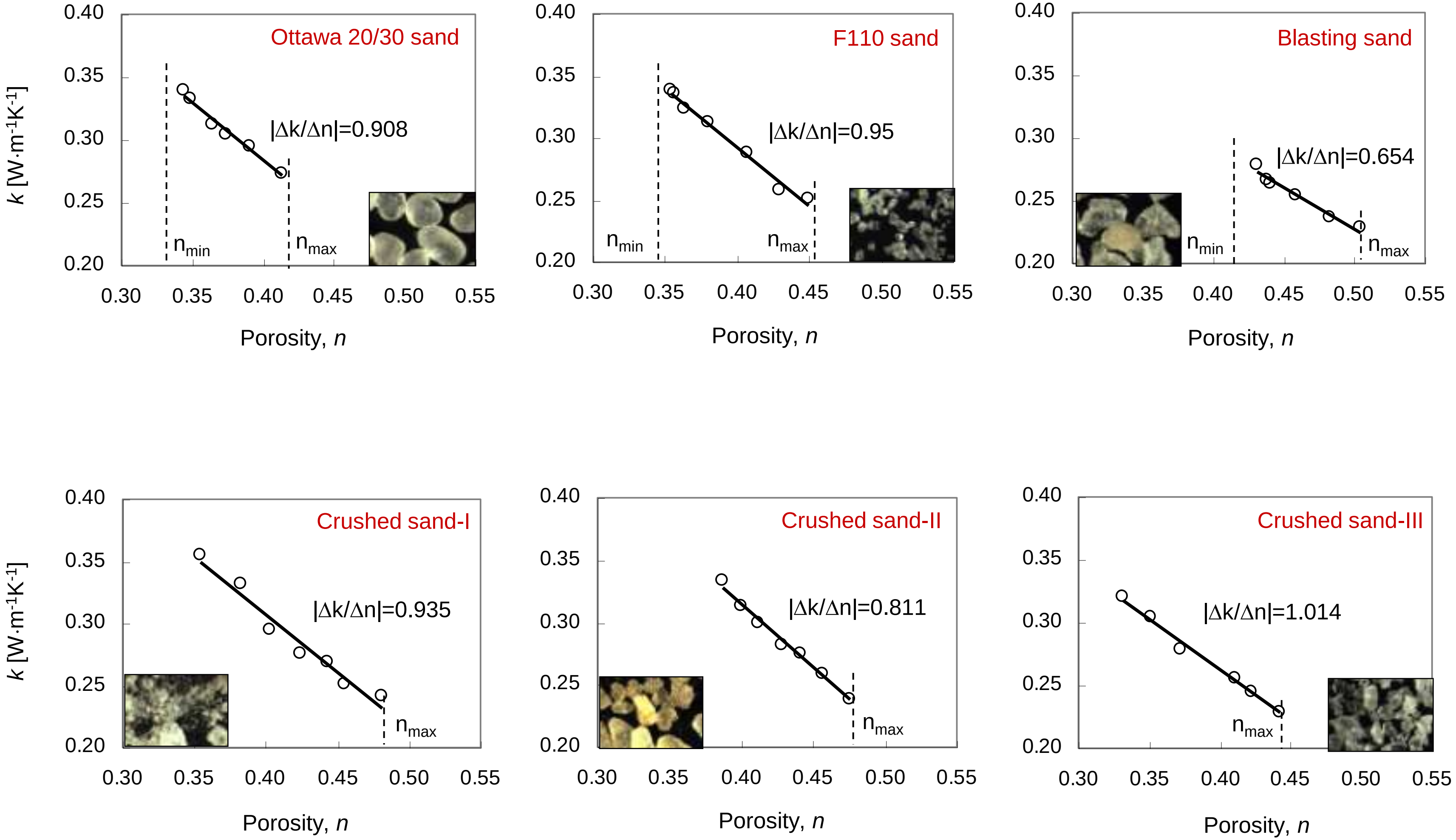
k= f(*contact quality*)

Thermal Conductivity: Dry vs. Wet Soils



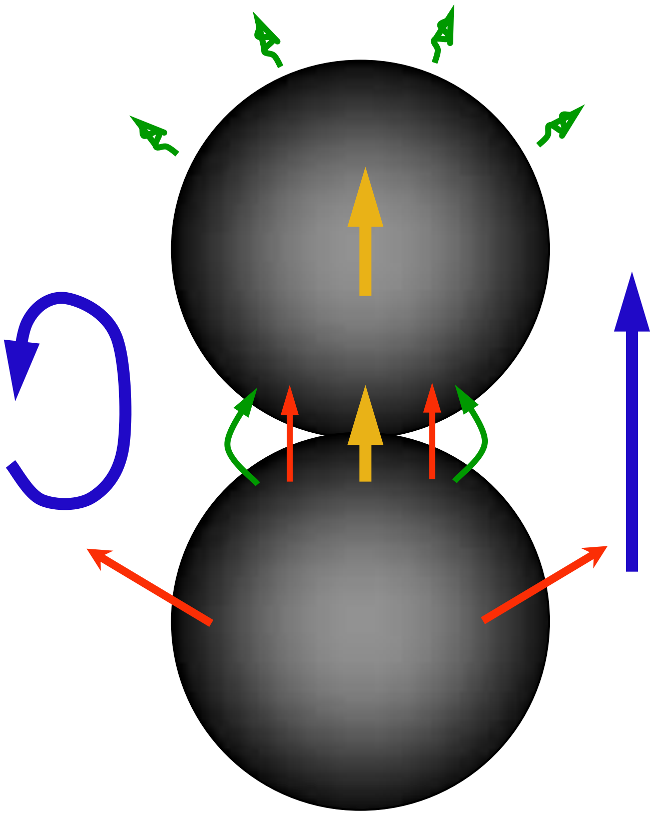
k= f(w, σ')

Thermal Conductivity: Dry Soils



k= f(n)

Thermal Conductivity in Soils



particle conduction
contact conduction

mineral
c#, n, σ’

radiation
particle-particle radiation

particle-fluid conduction
particle-fluid-part. cond.

pore fluid conduction
pore fluid convection

fluid, S%
D_{10}

Thermal Conductivity: Values

Material	k_T (W/mK)
Air	0.02
Water at 21 C	0.72
Ice at 0 C	2.2
Sand, dry	1.1
Sand, ω= 18% (unfrozen)	3.1
Sand, ω= 18% (frozen)	3.8
Clay, dry	0.9
Clay, ω= 25% (unfrozen)	1.2
Clay, ω= 25% (frozen)	1.5
Quartz	8.4
Stainless Steel	~20
Copper	400

$k_{gas} < k_{water} < k_{ice}$

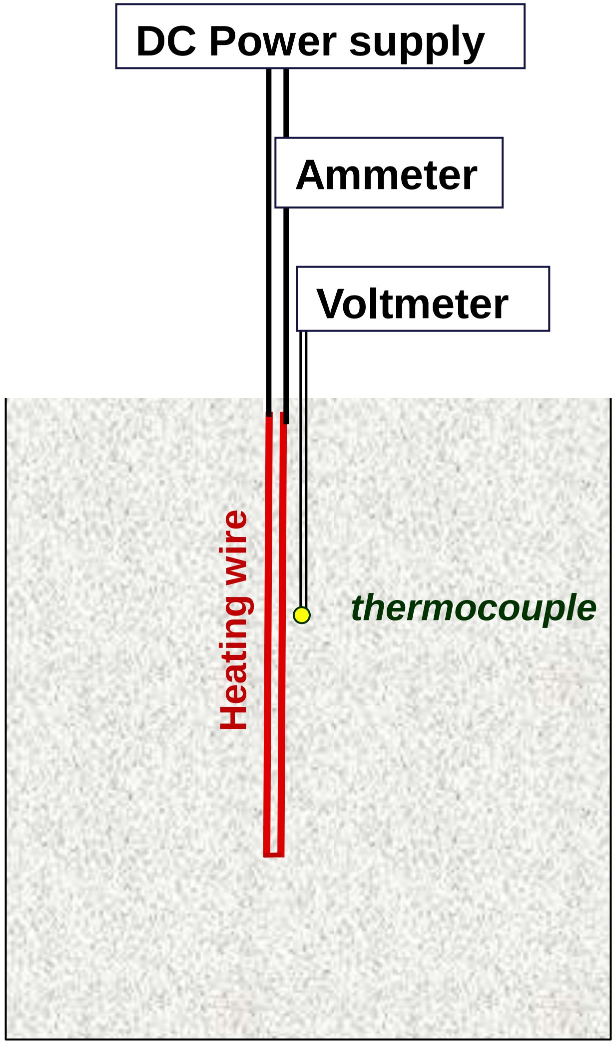
$k_{dry} < k_{wet} < k_{frozen}$

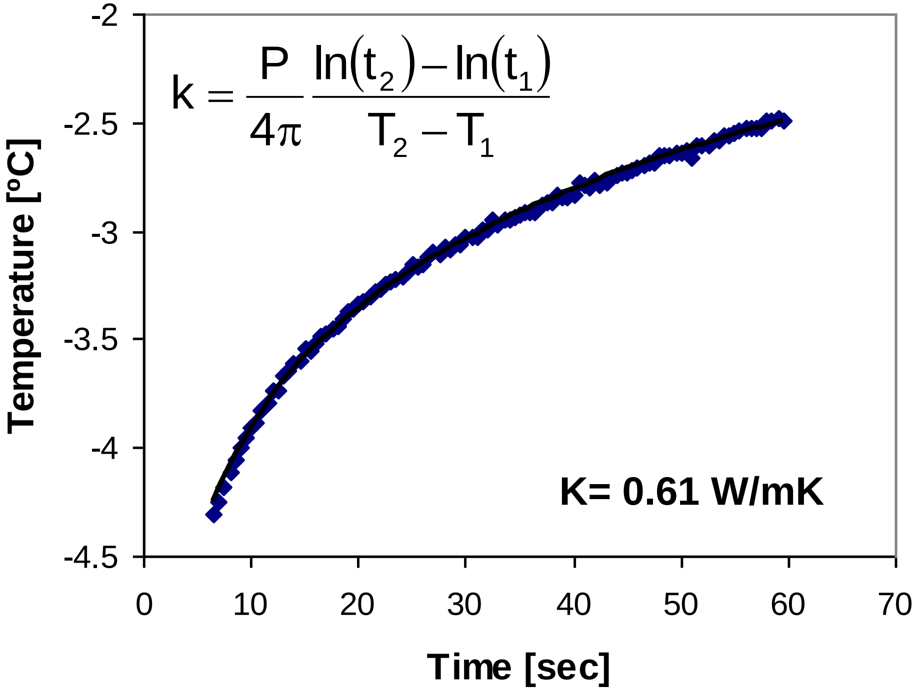
general trends

$k_{gas} < k_{dry} < k_{wet} < k_{frozen} < k_{min}$

$k_{clay} < k_{sand}$

Lab & Field: Needle Probe



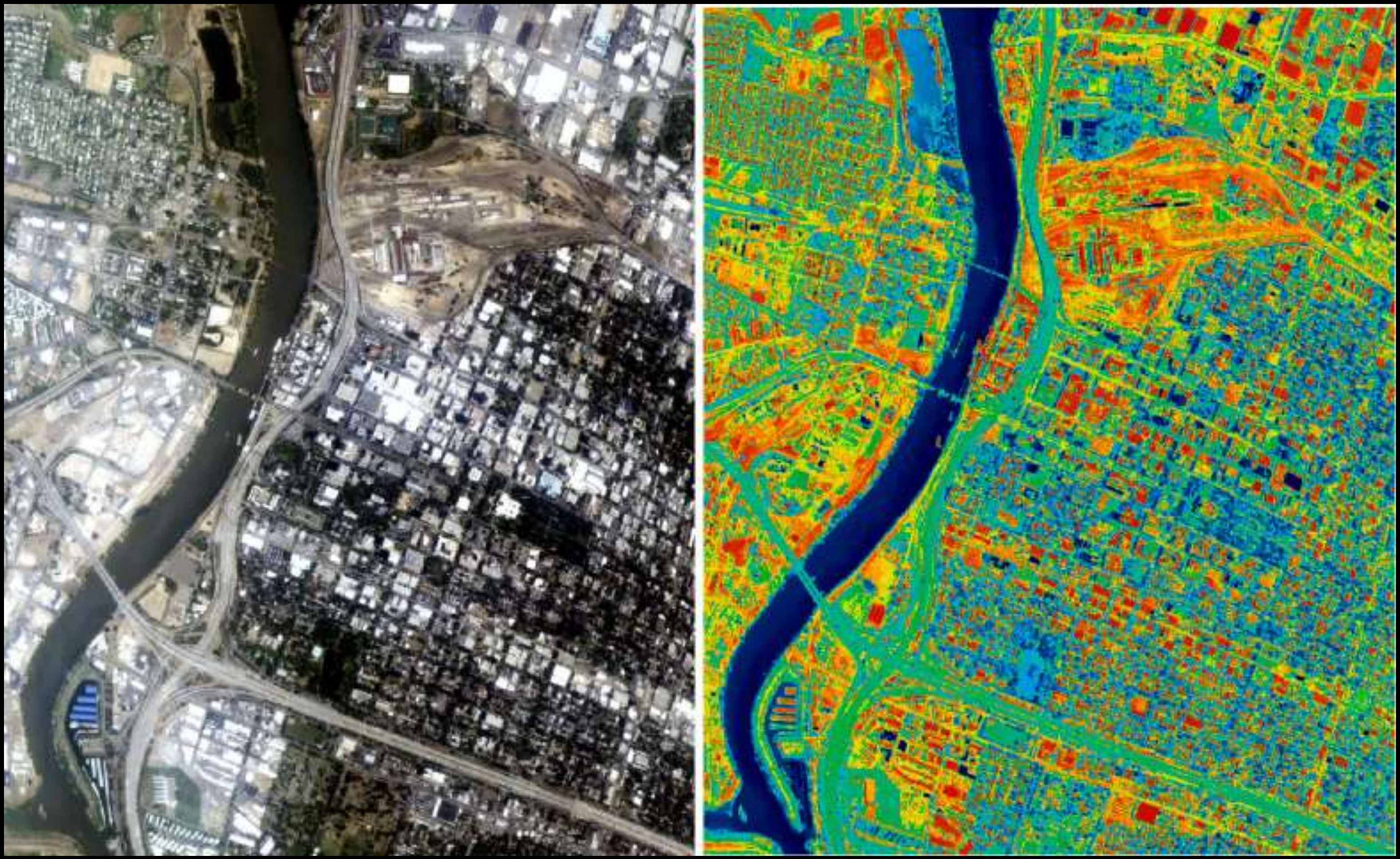


Application: GeoThermal

Narsilio & Johnston
Melbourne U.

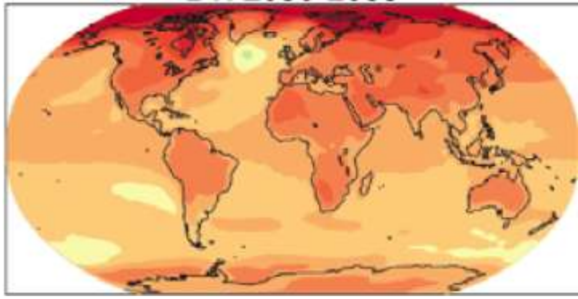
Application: Cities = Thermal Islands

Sacramento, California

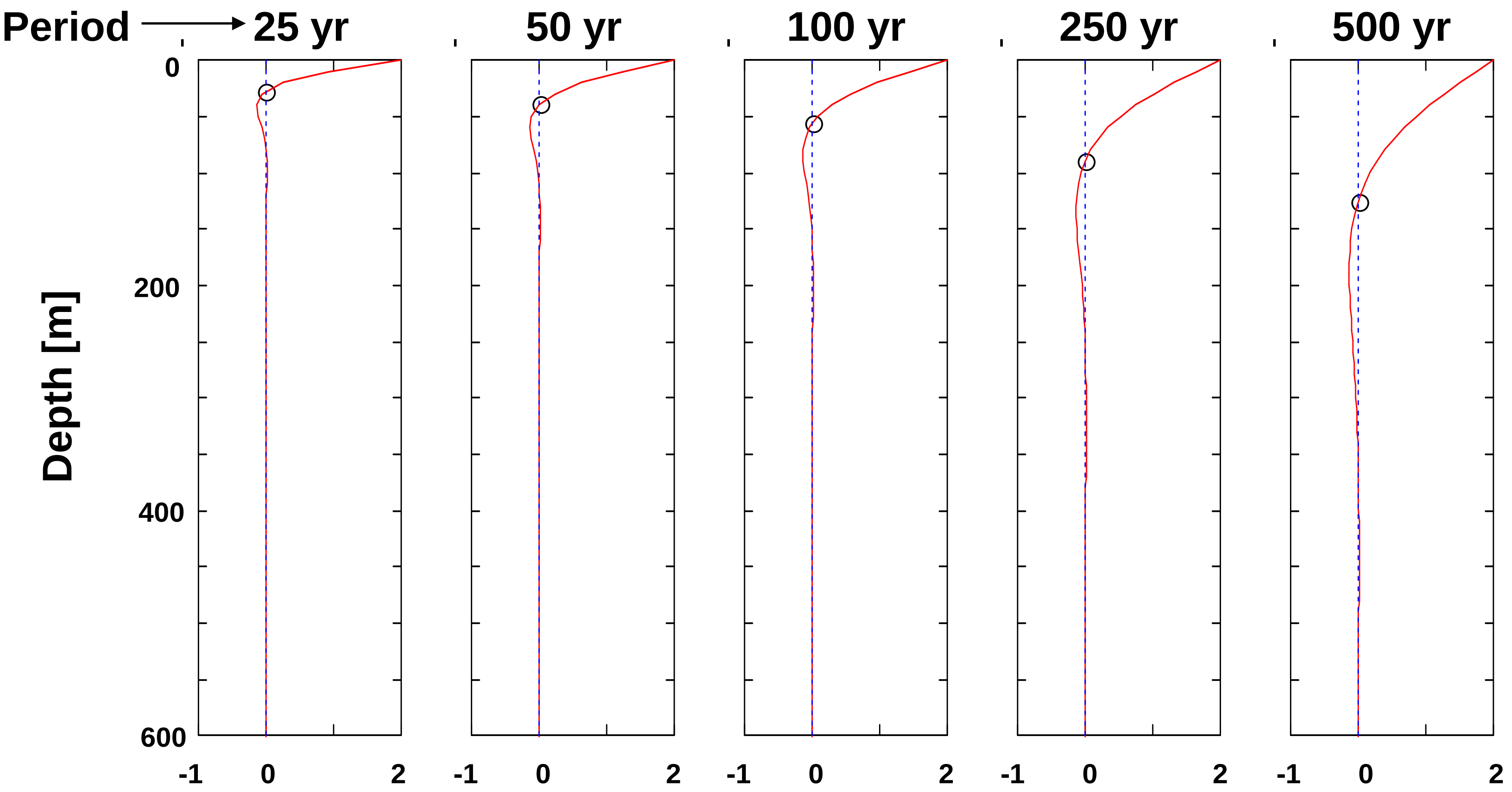


science.nasa.gov

Application: Climate Change



T_{atm}=Sinusoidal (2°C)



Summary: Thermal Properties

Conductivity k ↑	**Porosity n↓**
	Effective stress ↑ (heat transfer at contacts ↑)
	Water content
	Quartz content ↑
	Frozen
	Coarser grains
Implications	**Energy: Geothermal, Nuclear (foundations & waste), …**
	Climate change
	Urban settings

[Mechanical Waves]

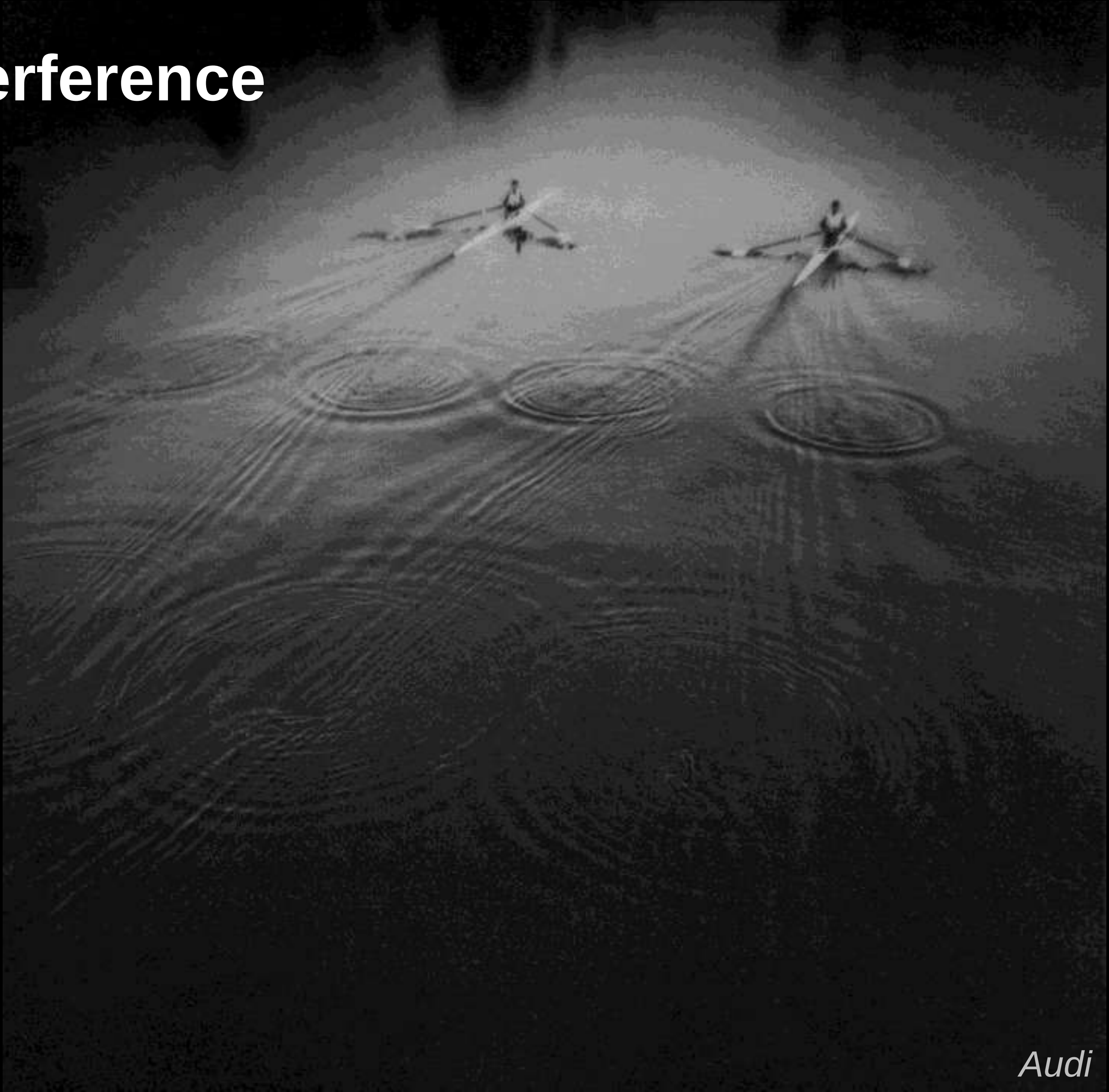
[Electromagnetic Waves]

[Thermal Phenomena]

Processing

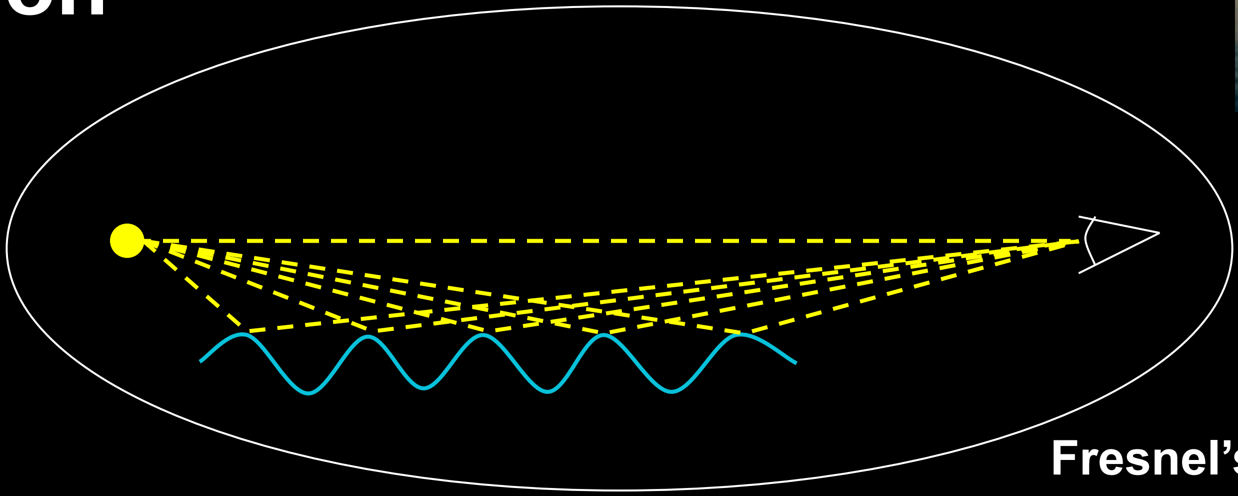
- **Wave phenomena**
- **Signal processing**
- **Inversion**

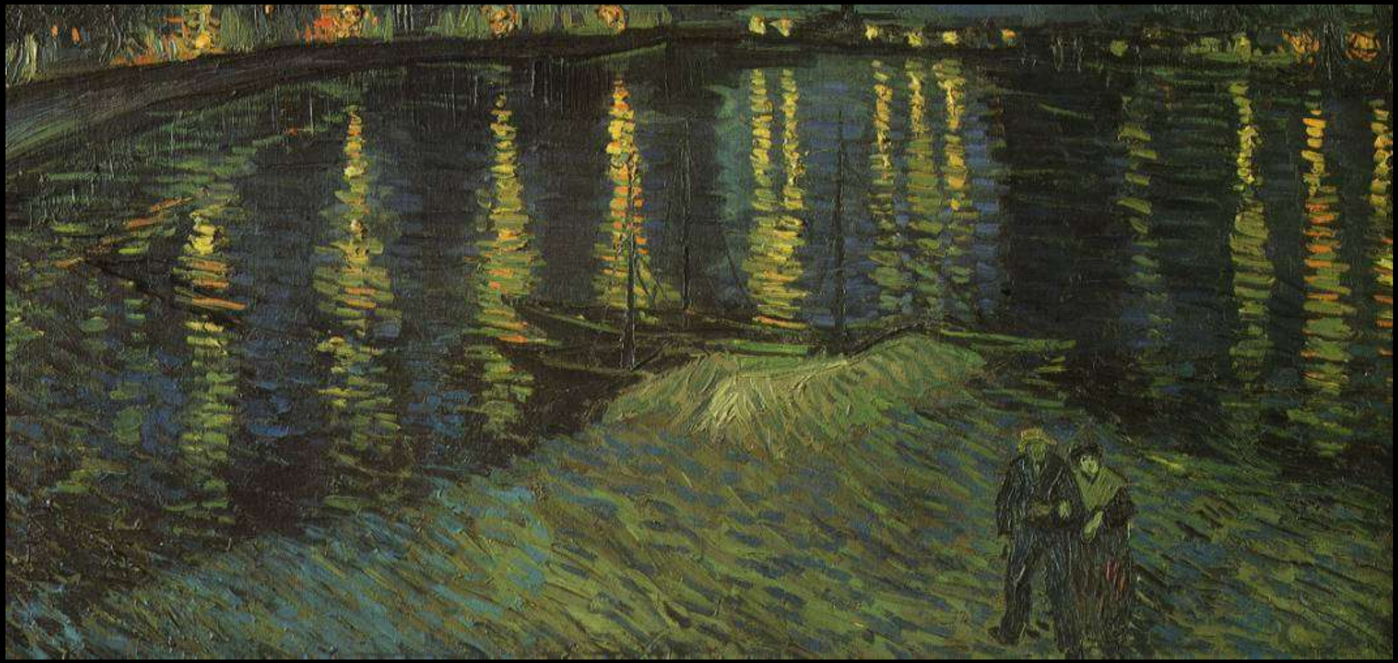
Interference



Audi

Reflection





van Gogh - La Nuit Etoilee

Scatter

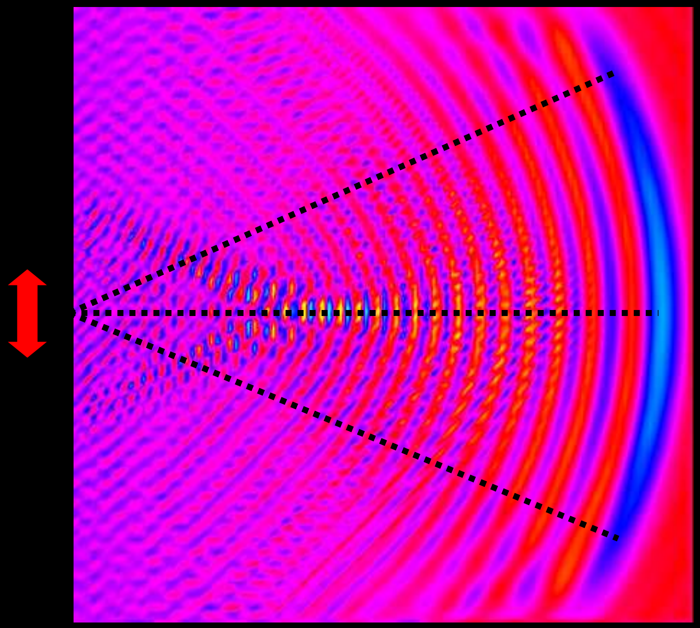
Microscopy: dark field illumination

St. Peter - Rome

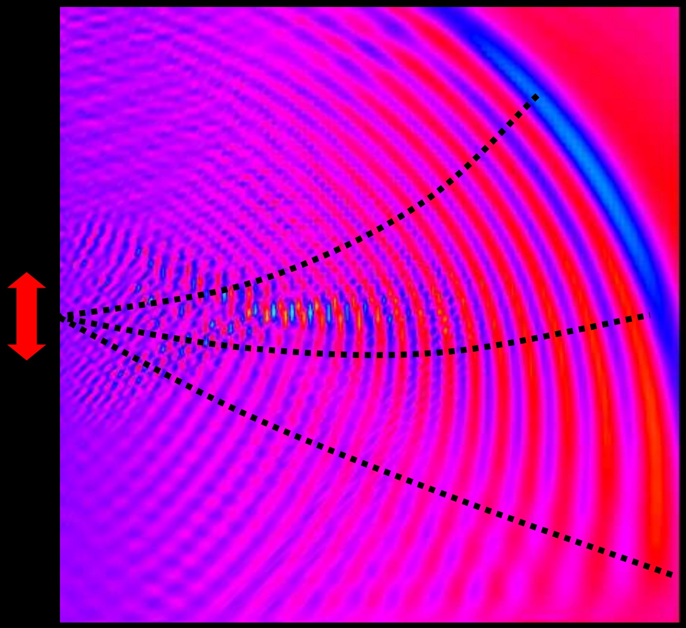
Diffraction Healing

defects in piles?   honeycombs in concrete?   tunnels (KMZ, US-Mx, Israel-Palestine)?

Vertical Heterogeneity

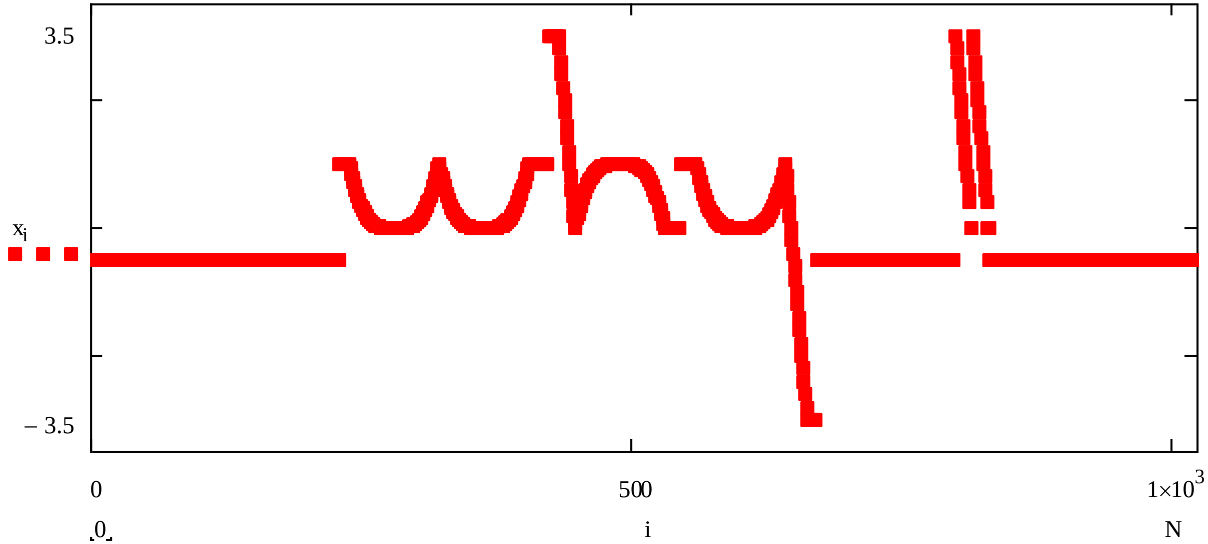


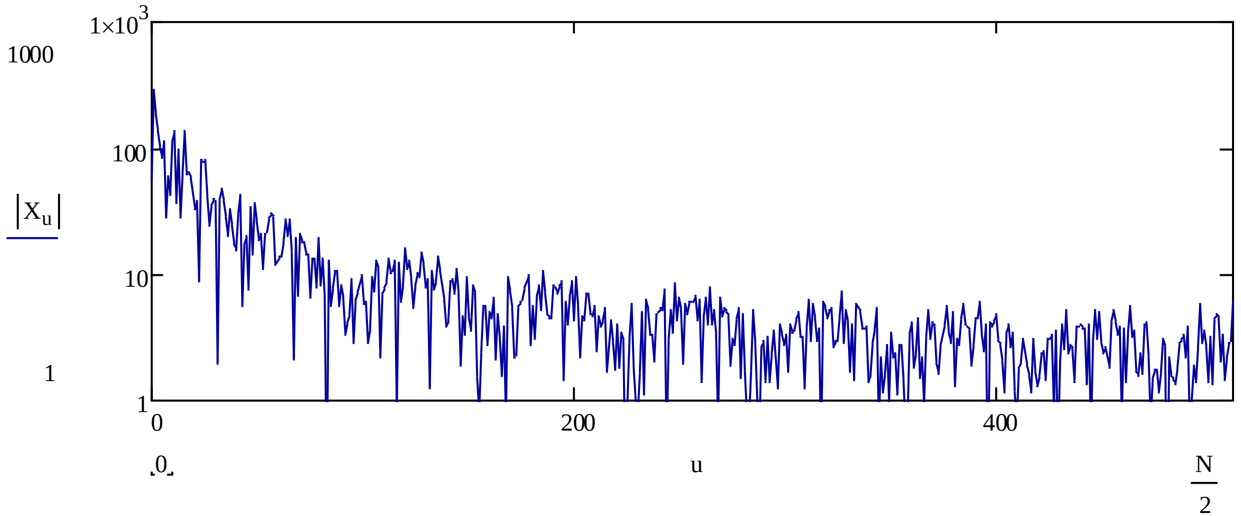
Homogeneous
Isotropic
Linear Elastic



Vertically heterogeneous
Cross-anisotropic
Linear Elastic

Signal Processing: FFT

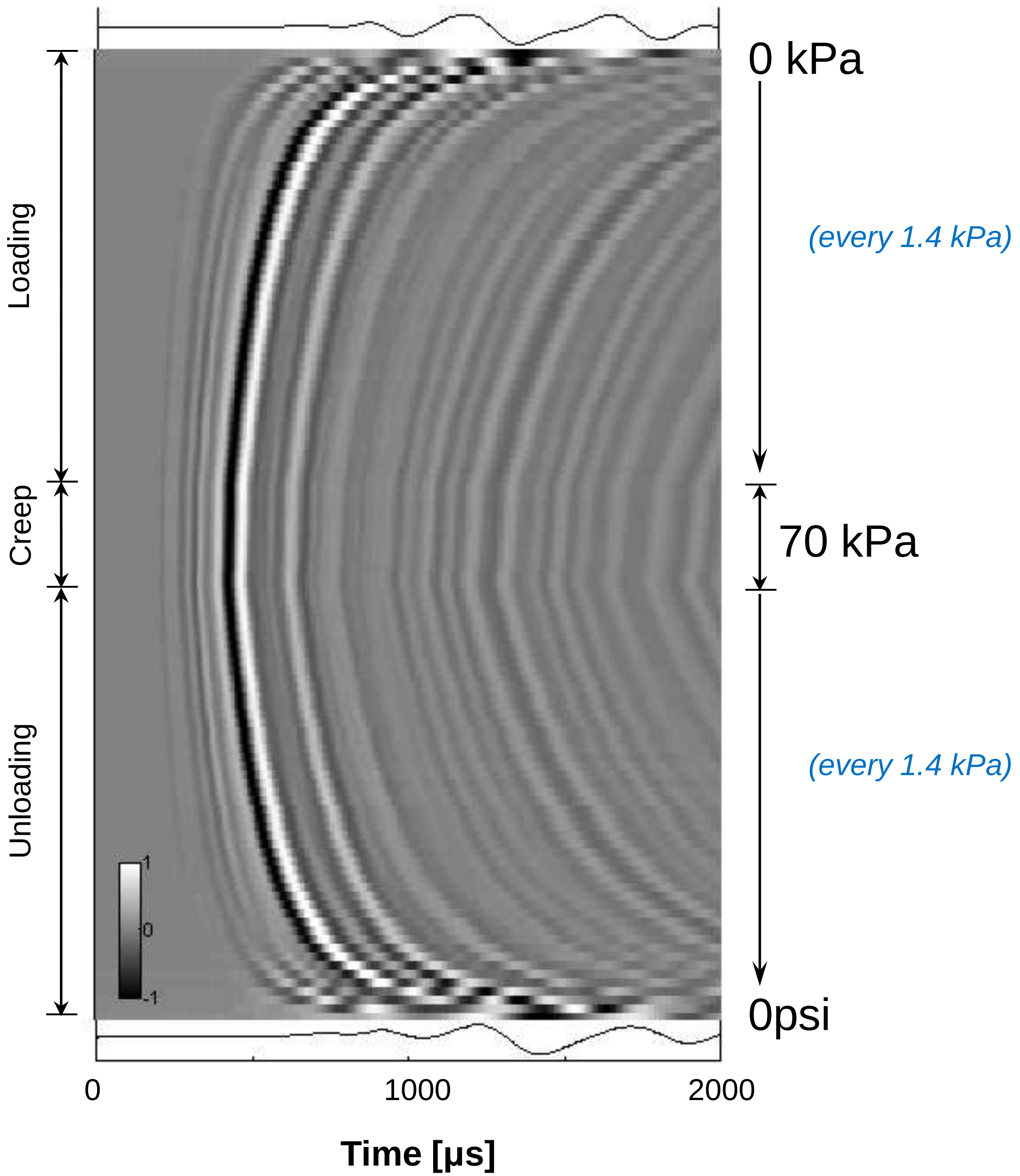




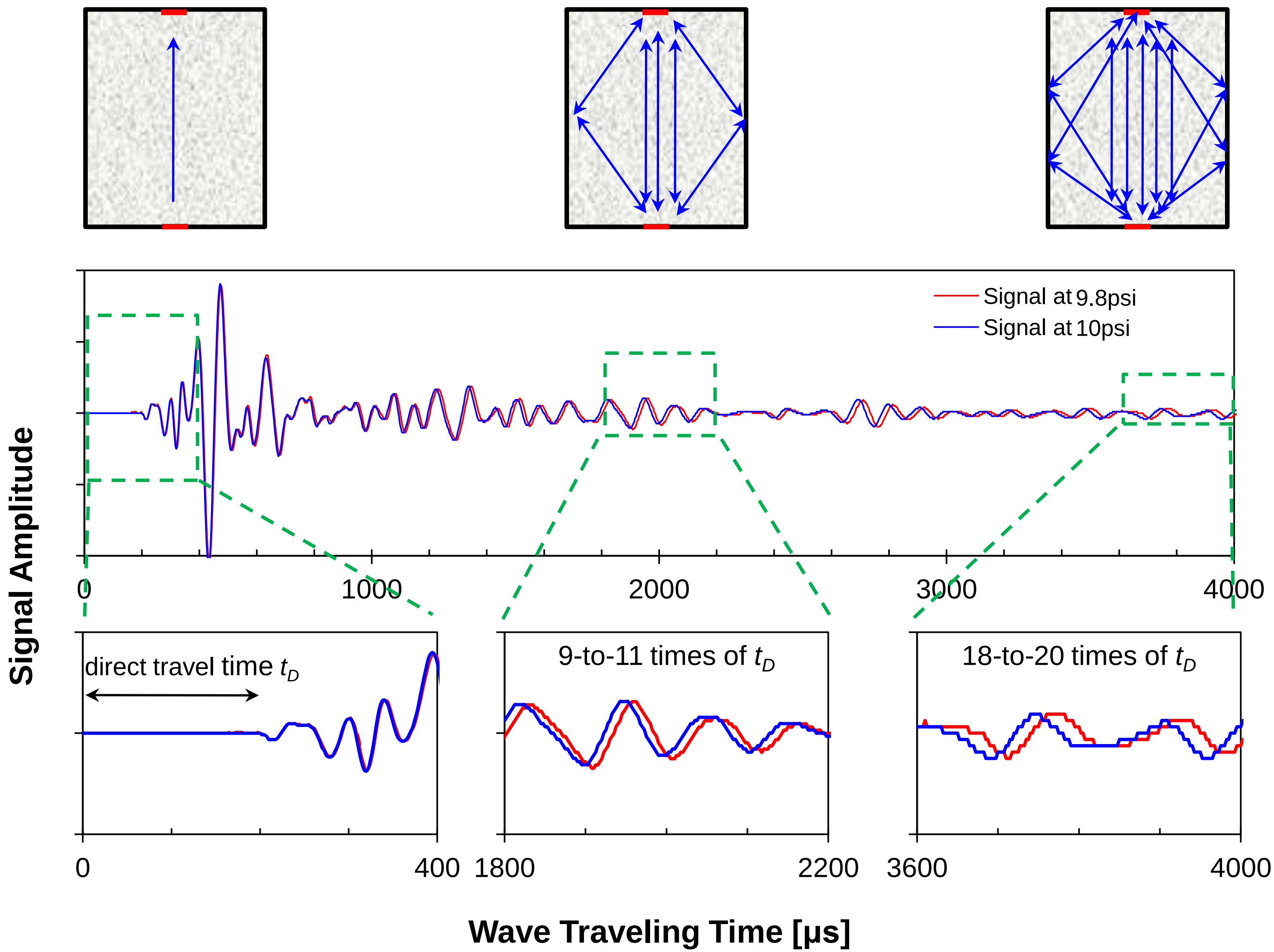
Fourier Transform = curve-fitting the signal using the Fourier Series (caution with BE !)

Signal Processing: Tracking Small Changes

dry Ottawa sand

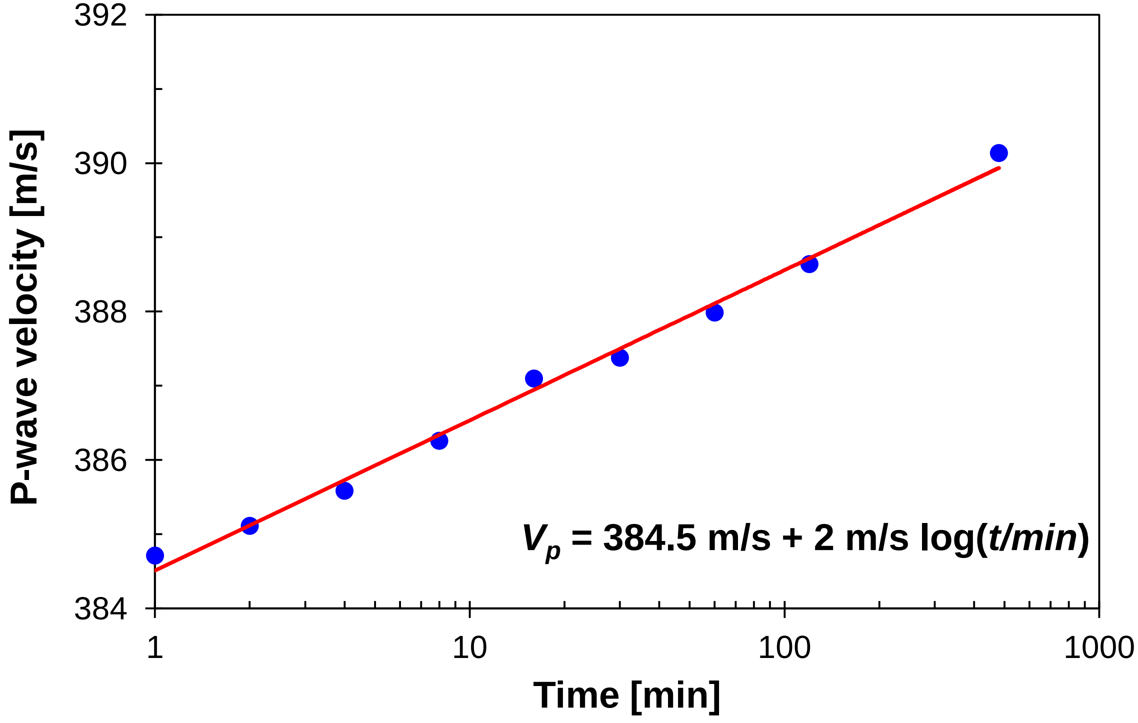


Coda Wave Analysis: Creep in Dry Sand



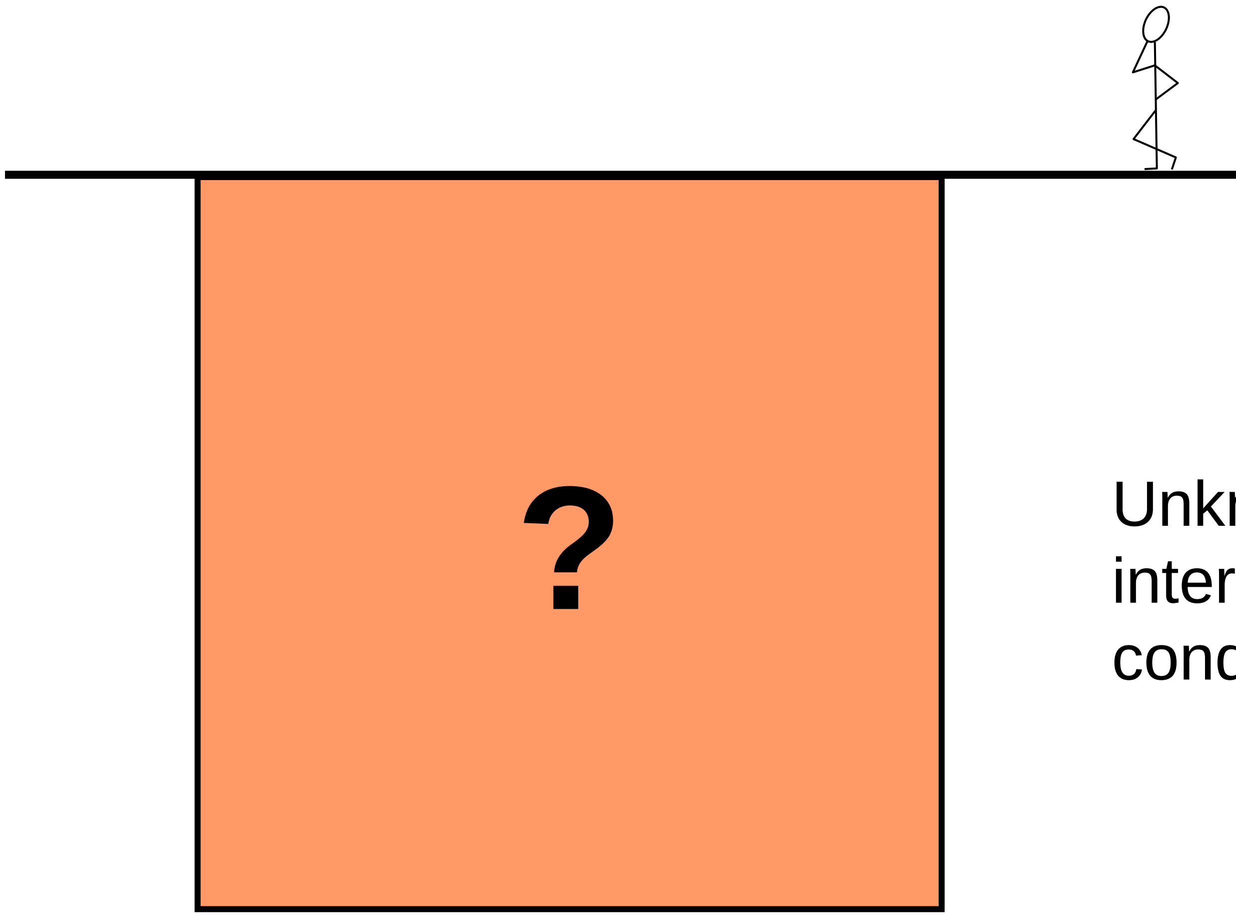
See F. Wuttke

Coda Wave Analysis: Creep in Dry Sand

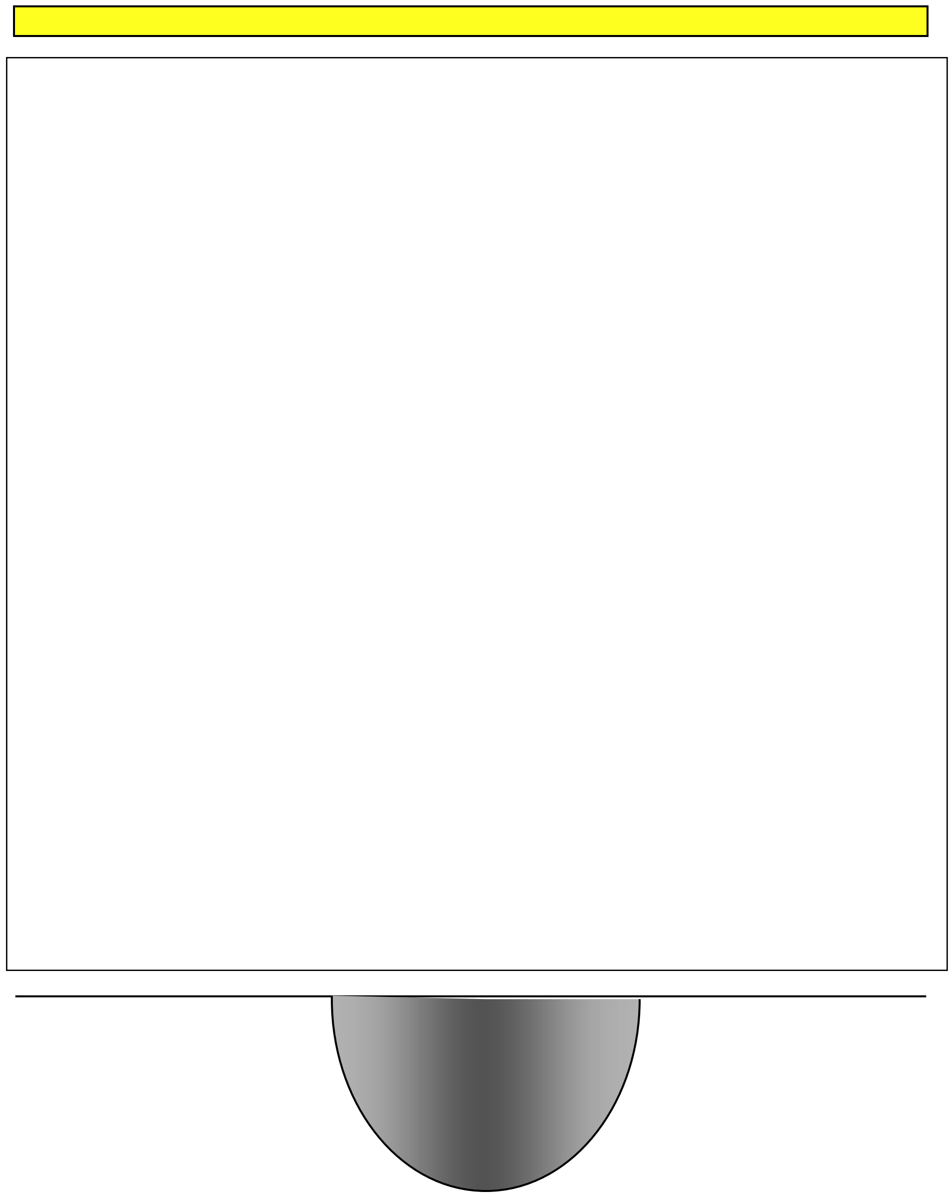


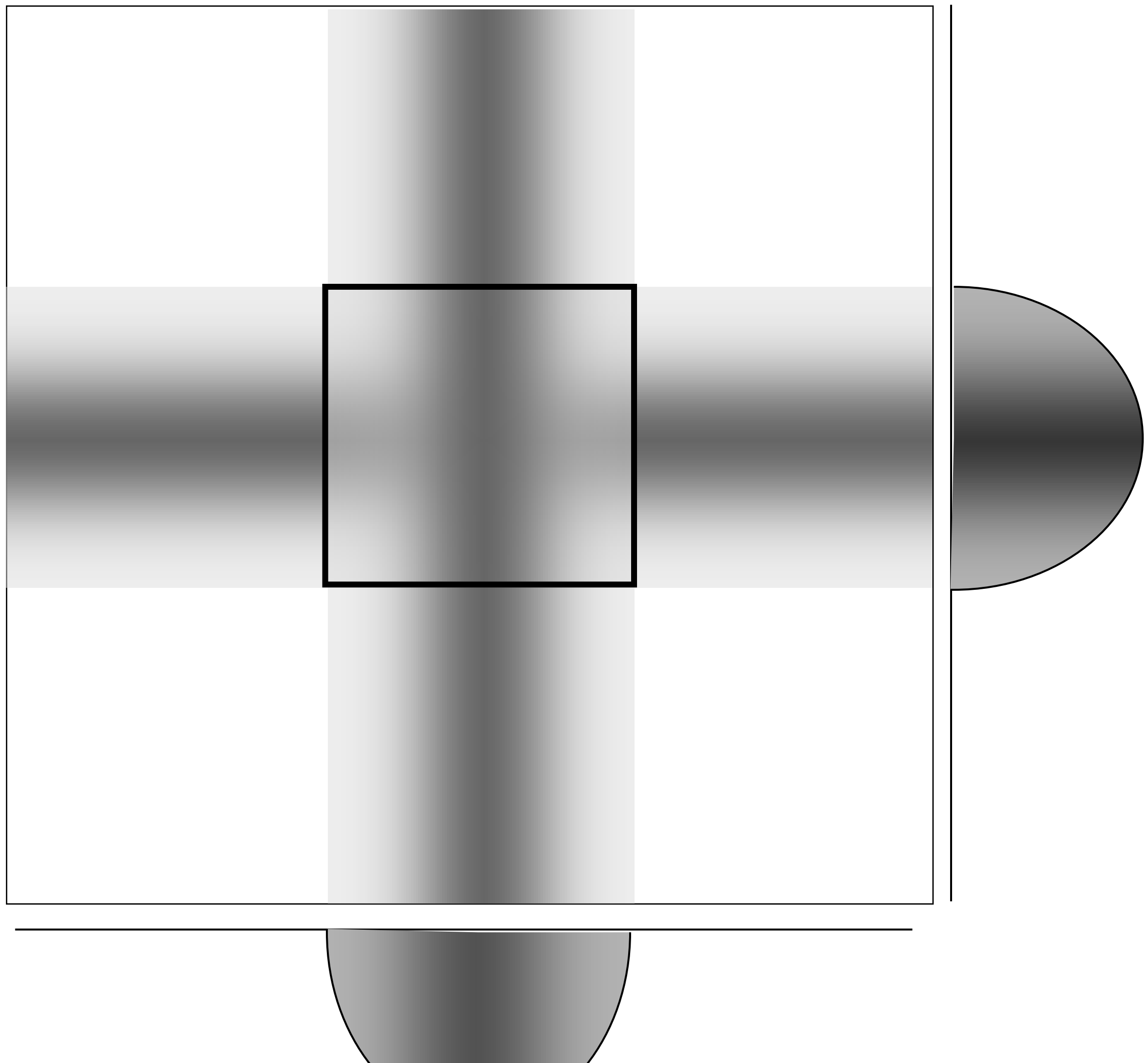
S. Dai

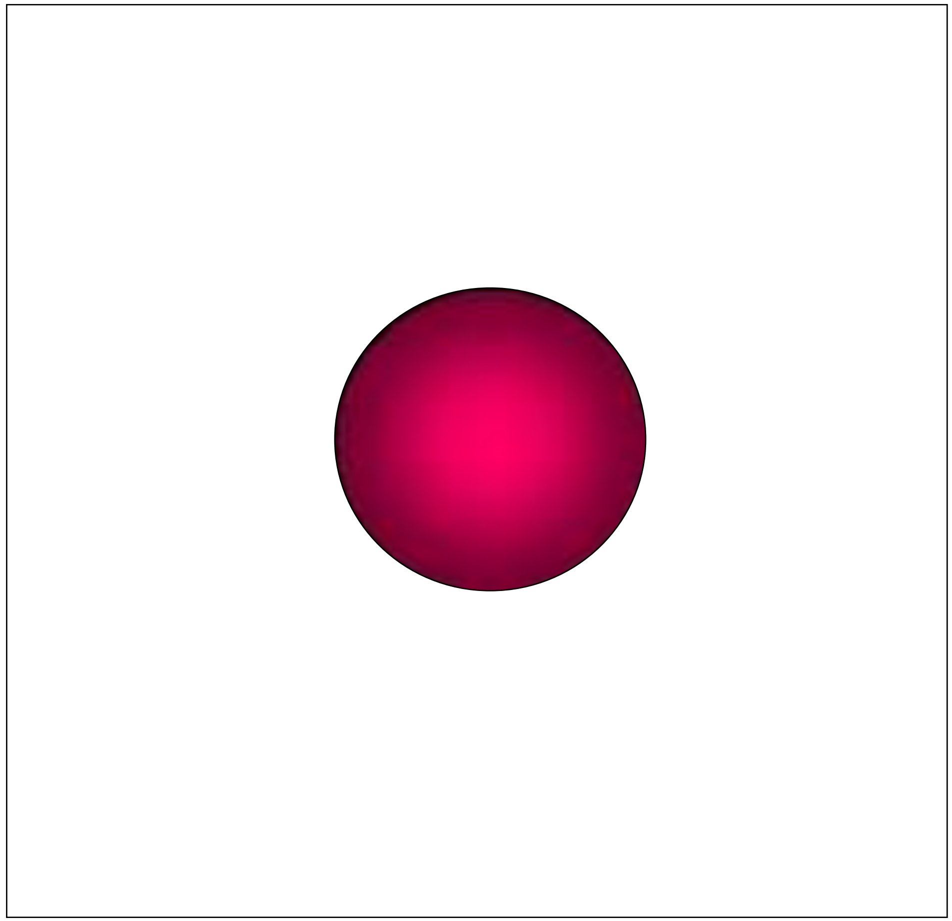
Inversion: Tomography



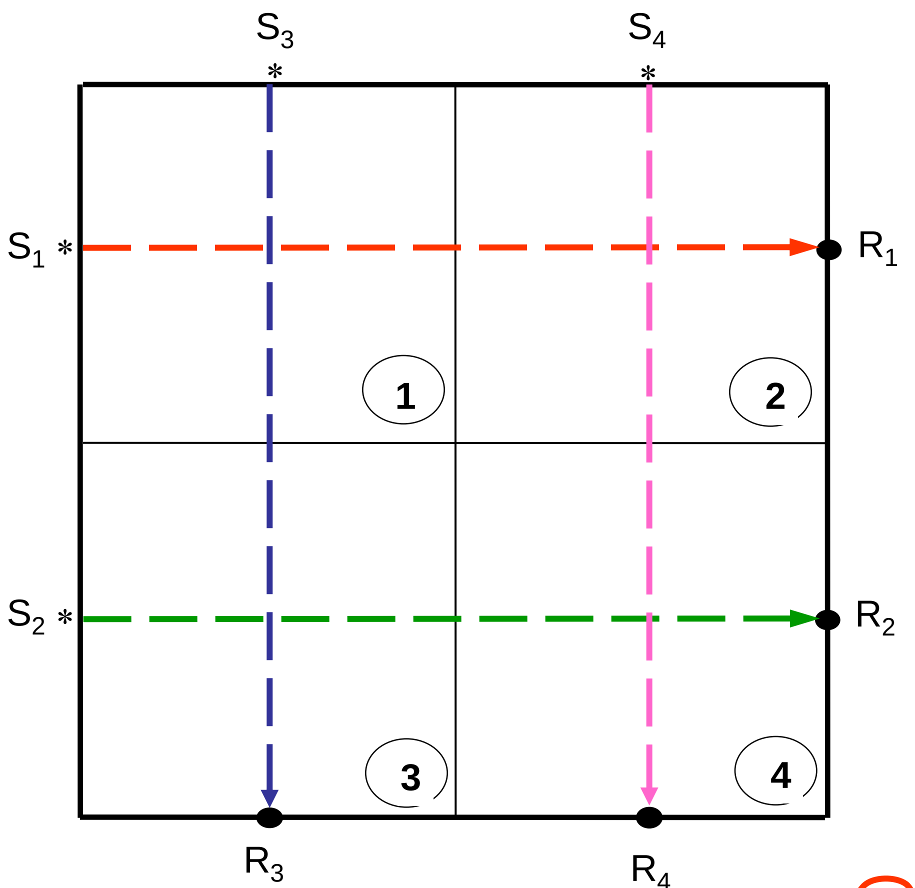
Unknown
internal
conditions







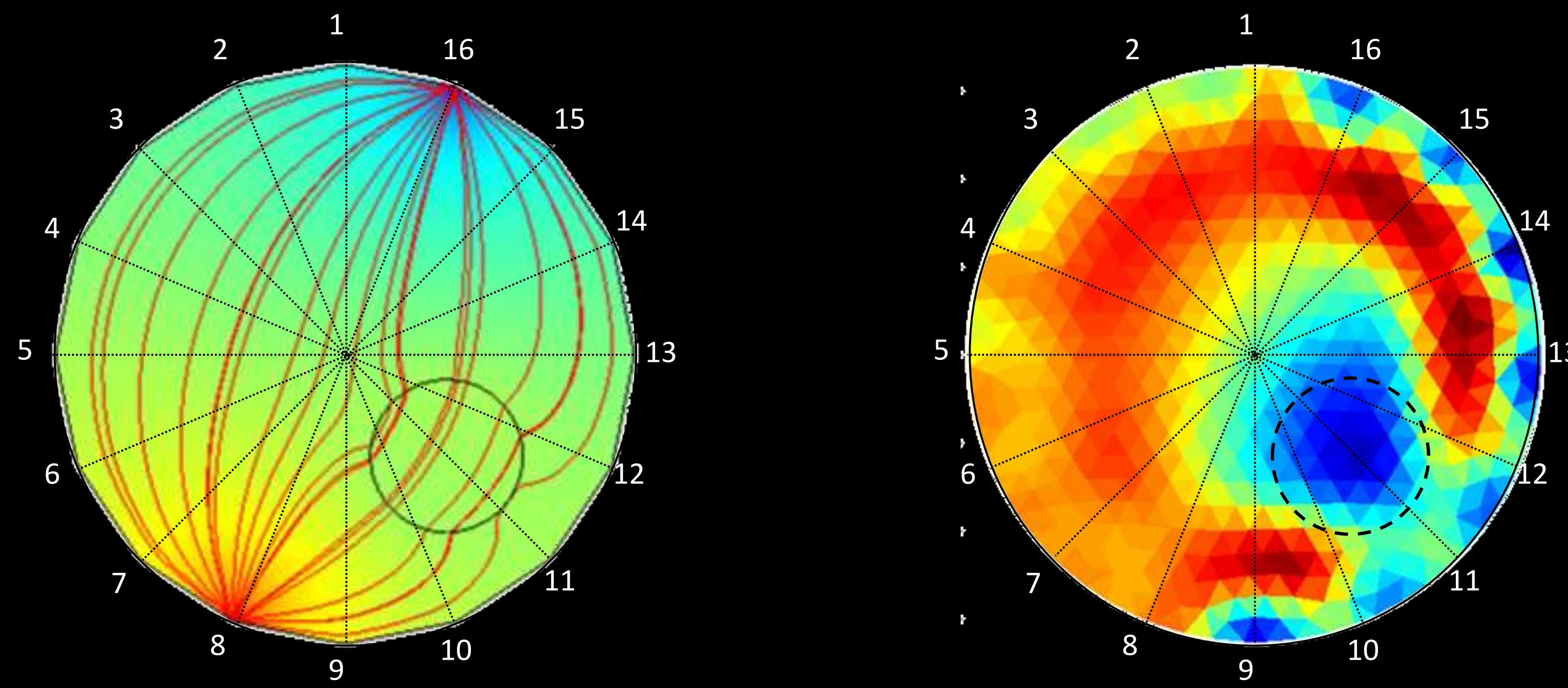
Mathematically…



$$\begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \end{bmatrix} = \begin{bmatrix} \ell_{1,1} & \ell_{1,2} & 0 & 0 \\ 0 & 0 & \ell_{2,3} & \ell_{2,4} \\ \ell_{3,1} & 0 & \ell_{3,3} & 0 \\ 0 & \ell_{4,2} & 0 & \ell_{4,4} \end{bmatrix} \cdot \begin{bmatrix} 1/V_1 \\ 1/V_2 \\ 1/V_3 \\ 1/V_4 \end{bmatrix}$$

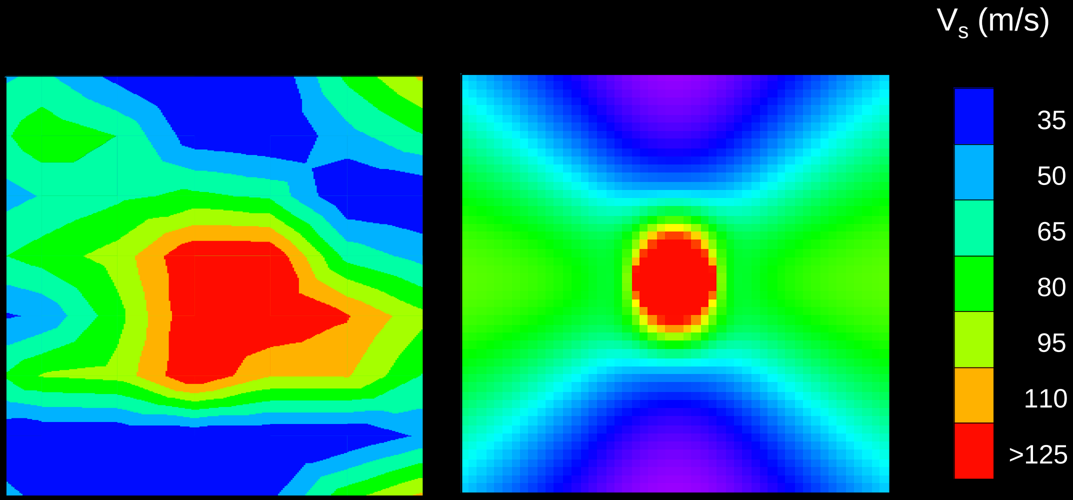
Numerical and Experimental Study

high conductivity anomaly



JY Lee
see also Fotti et al.

Around tunnels: velocity tomograms



Pixel Parametric

Summary: Processing

Waves: complex phenomena

yet… information-rich

Signal Processing:

needed to extract information

may be misleading…

Inverse Problems:

how much information is in the data?

ill-posed ?

Closing Thoughts

Mechanical Waves

Electromagnetic Waves

Thermal Phenomena

Processing

Geophysical methods extend our senses…

Mechanical waves

V_s: skeletal stiffness (σ', cement, suction)

V_P: saturation

Electromagnetic Waves

κ: volumetric water content (porosity if S=100%)

σ: pore fluid conductivity (and… specific surface)

μ: ferromagnetism

Thermal:

Effective stress & water content (frozen?)

Mechanical waves, EM waves and thermal:

Complementary information

Physically sound concepts

Parameters critical to geotech design

Low perturbation ➔ process monitoring

Boundary measurements ➔ tomography

Spatial variability and anisotropy

Some complexity… but information rich

Add sensors to all cells

CAUTION: processing …

Process Monitoring:

Sedimentation
Ageing
Drying – Unsaturation
Ionic diffusion
Dynamic energy coupling
Stochastic resonance
Ground modification
Freezing
Failure
Fabric anisotropy

Pressure diffusion
Thixotropy and Creep
Cementation / de-cementation
Chemo-osmosis
Seismic-electric coupling
Liquefaction
Mixed fluid-phase
Hydrates
Stress tomography
Spatial variability

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Organizers

Thank you !