RUTGERS
NEWARK

Soil Physics of Leak Detection using Geoelectrical Methods

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LANCASTER
UNIVERSITY

What can geophysics really offer?

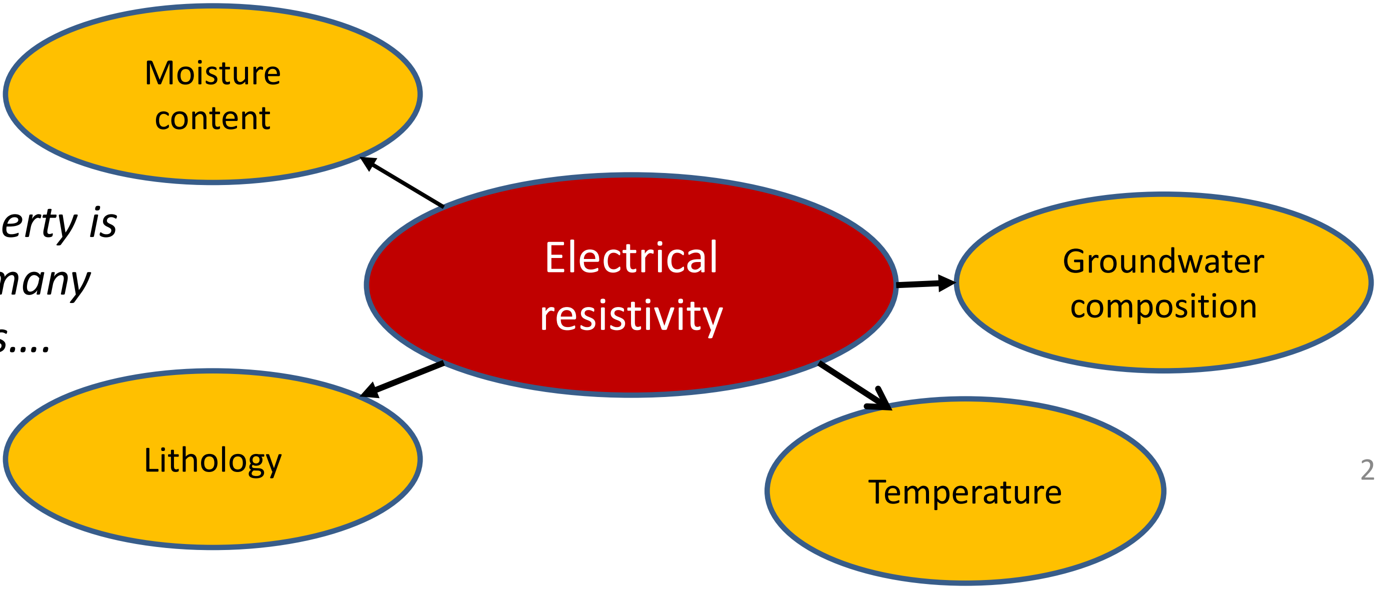
PROS

- non invasive sampling
- spatially continuous data
- relatively inexpensive data acquisition

CONS

- **geophysical properties are an indirect function of the earth properties to be determined in site investigations**
- Highly sensitive to infrastructure

The geophysical property is often dependent on many subsurface properties….



Electrical resistivity

Moisture content

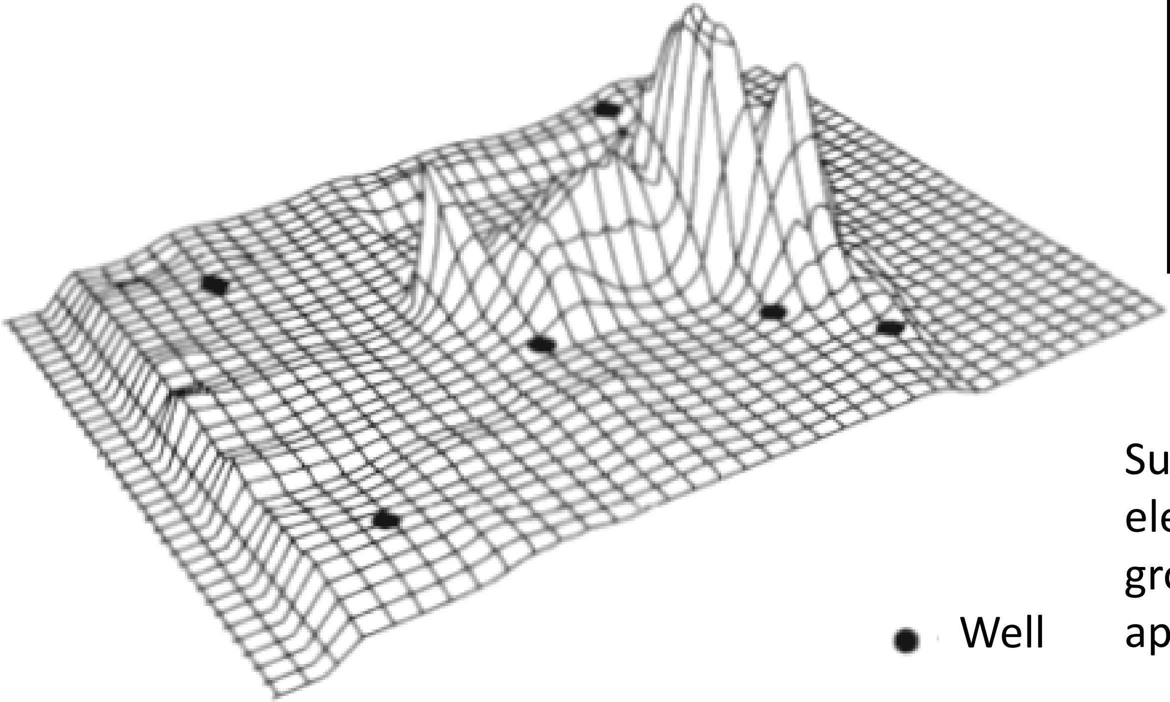
Groundwater composition

Lithology

Temperature

An old example of the value of geophysics

A contaminant plume undetected by 6 drilled wells is revealed following an inexpensive and efficient **electromagnetic** survey.



Geonics EM31 instrument used in this survey

Successful survey as [1] strong electrical property contrast due to groundwater contamination [2] appropriate instrument used

Benson, R.C. and Noel, M.R., 1983. Geophysical techniques for surveying buried wastes and waste investigation. Report No. 68-03-3050, Environmental Monitoring System Laboratory. Office of Research and Development, United States Environmental Protection Agency, Las Vegas.

Some basic considerations

IMAGING MIGRATION OF LEAK CONSTITUENTS WITHIN THE SOIL

BOTH

Is there a strong

DETECTING

Is there a geophysical technique with the spatial

THESE QUESTIONS SHOULD BE ADDRESSED VIA SYNTHETIC STUDIES **PRIOR TO EXPENDITURE IN THE FIELD**

source to measurable perturb the electrical potentials?

If “no” then do not pursue a geophysical survey!!!

Buyer beware of bad geophysics…..

There are many examples of bad geophysical survey practice and <u>misinterpretation</u>

THESE CAN BE AVOIDED IF THE RIGHT QUESTION IS ADDRESSED……

this interpretation is physically impossible

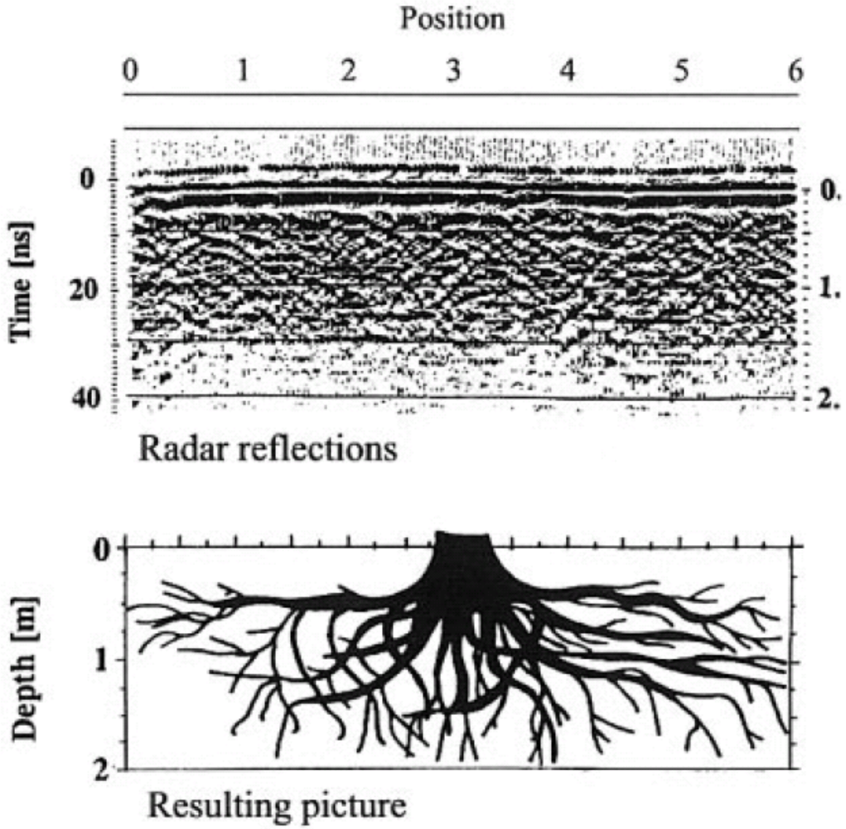
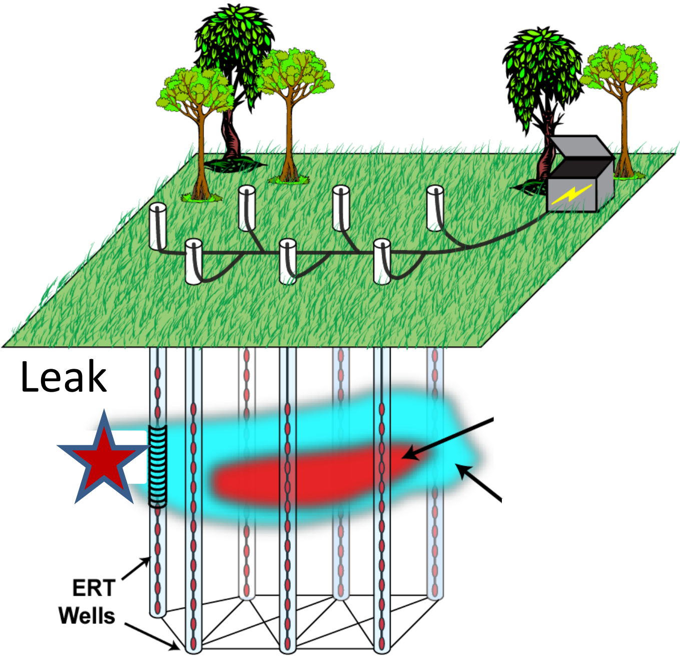


Fig. 1. Upper panel: an example of the primary radar image (radar reflections in the soil along a defined path across analysed roots), and lower panel: the resulting picture of the root system of large winter oak—*Quercus petraea* (Mattusch) Liebl. (modified after Hruška *et al.*, 1999).

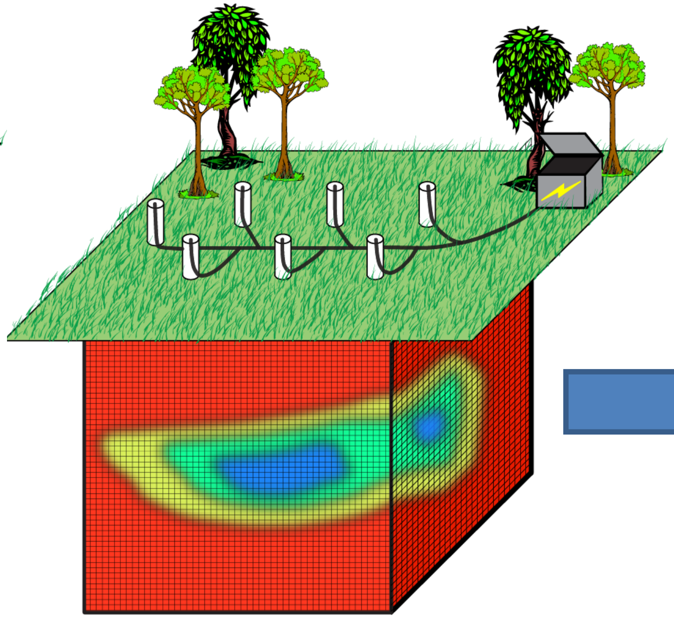
Published in Nadezhdina and Cermak, "Instrumental methods for studies of structure and function of root systems of large trees" et al.
Journal of experimental botany 2003

How much information do you need?

GEOPHYSICAL SURVEY OVER LEAK LOCATION



GEOPHYSICAL IMAGE OF LEAK DISTRIBUTION?

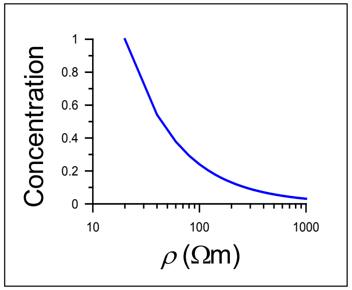


Qualitative information

ESTIMATES OF CONTAMINANT CONCENTRATION?

very uncertain!

PETROPHYSICAL TRANSFORM



Quantitative information

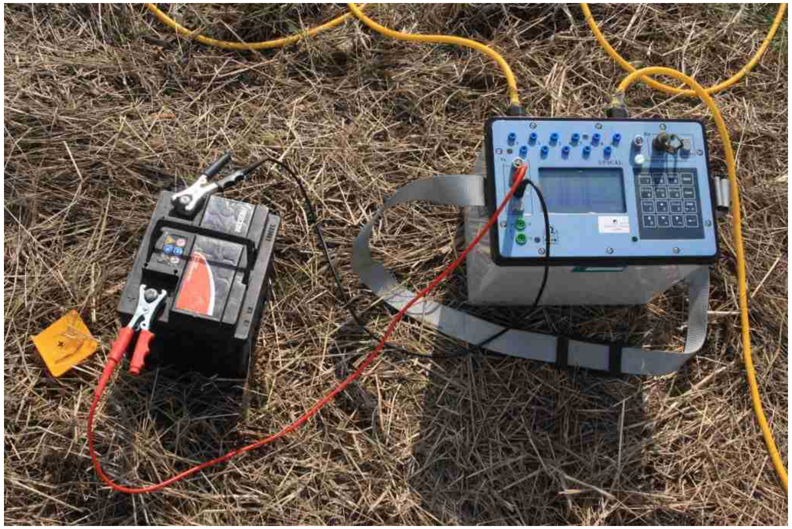
Whereas it may be possible to generate informative qualitative images of contaminant distribution, reliable quantitative information may be difficult to achieve

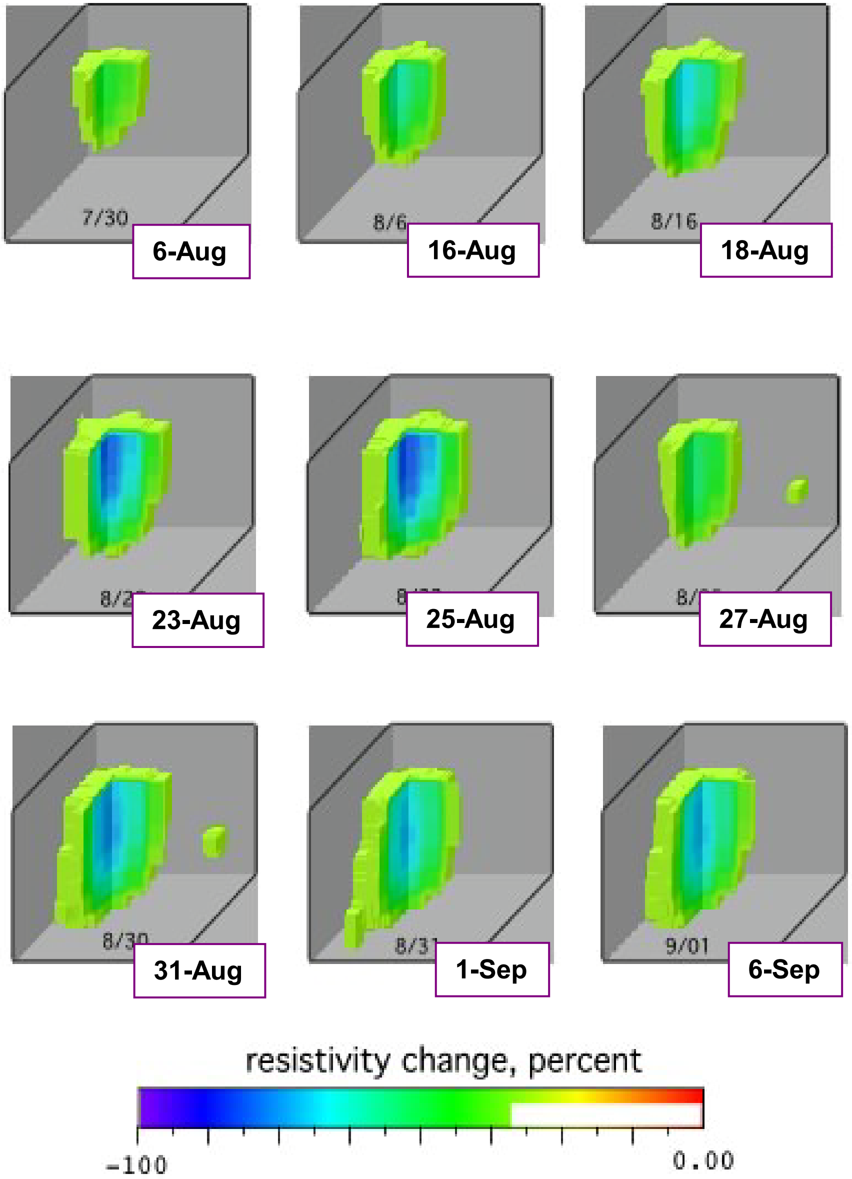
Image: Fred Day-Lewis, U.S.G.S., Storrs, CT

TIME LAPSE RESISTIVITY

May capture the movement of contaminants in the subsurface – but it requires a lot more investment and data processing

Inversion methods designed to solve for (often small) changes in resistivity relative to some background condition

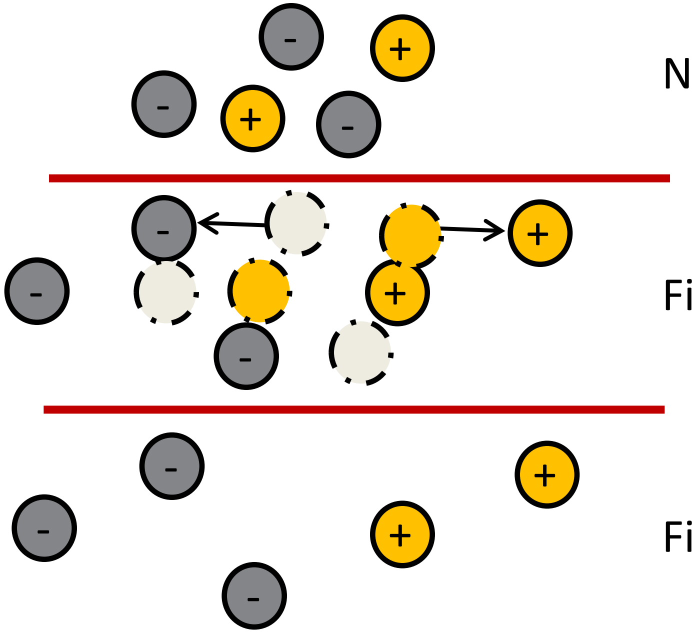




In 2003 a "blind trial" was conducted and reported in Daily et al.(2004). A total of 54 m^3 of sodium thiosulfate was leaked from a number of locations over a period of 110 days.

RESISTIVITY PETROPHYSICS BASICS

Conduction Currents



No Field

Field applied

Field removed

Current density

Electric field

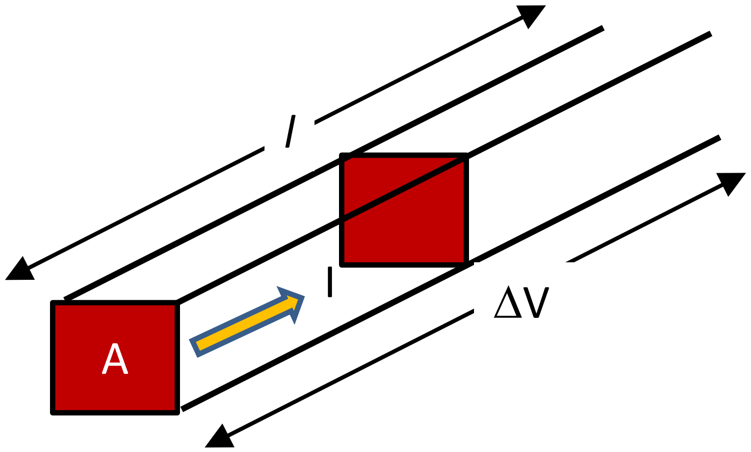
$$\mathbf{J} = \sigma \mathbf{E}$$

σ= electrical conductivity:

a measure of a material's ability to conduct an electric current

Electrical resistivity (ρ)

Quantifies resistance a material exerts to the flow of electric charge



property of material

$$R = \frac{\Delta V}{I} = \frac{1}{\sigma}\left(\frac{l}{A}\right) = \rho\left(\frac{l}{A}\right)$$

$$\sigma = \frac{1}{\rho}$$

geometric factor

RESISTANCE UNITS: volt/ampere = Ohms

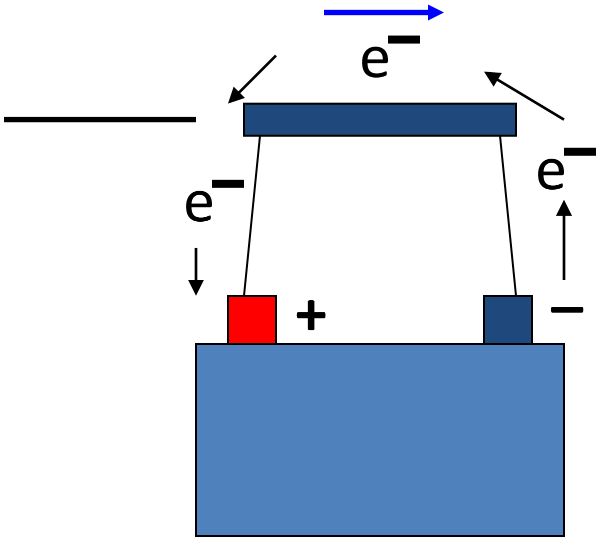
RESISTIVITY UNITS: Ohm m

How does electrical current flow?

- Electrical current:

Movement of charge

direction of current flow



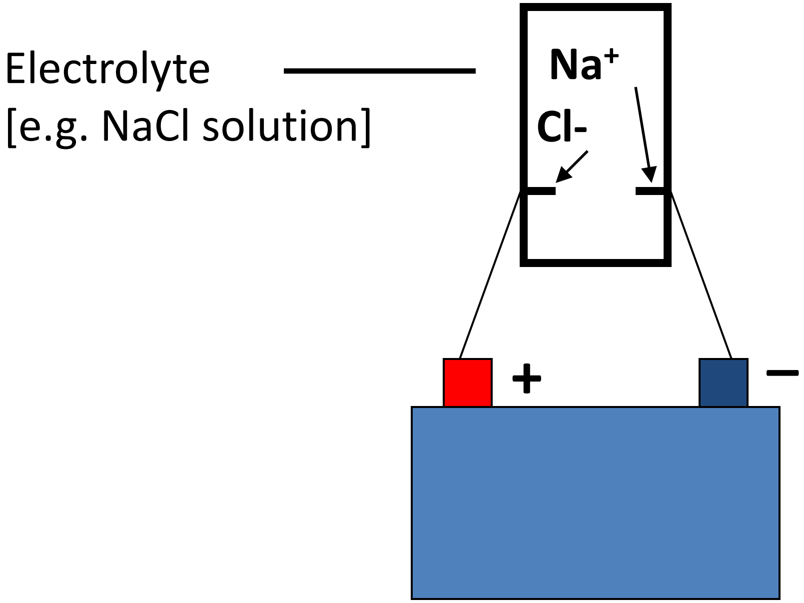
electronic conductor

- Electronic: electron mobility
- Ionic (Electrolytes): ionic mobility

How does electrical current flow in the earth?

- Electrolytic (water)

✓

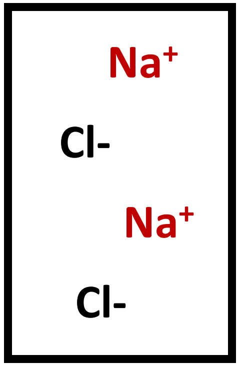


- Surface conduction - ionic charges at mineral-fluid interface are also mobile

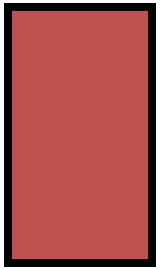
Electrical conductivity

- Conductivity (σ): the ability of a material to conduct electric current
- Resistivity (ρ): the reciprocal of conductivity

$$\sigma = \frac{1}{\rho}$$



NaCl solution - able to conduct



Vacuum - unable to conduct

Conductivity of electrolyte (σ_w) increases with ionic concentration

Case 1: Only electrolytic conduction

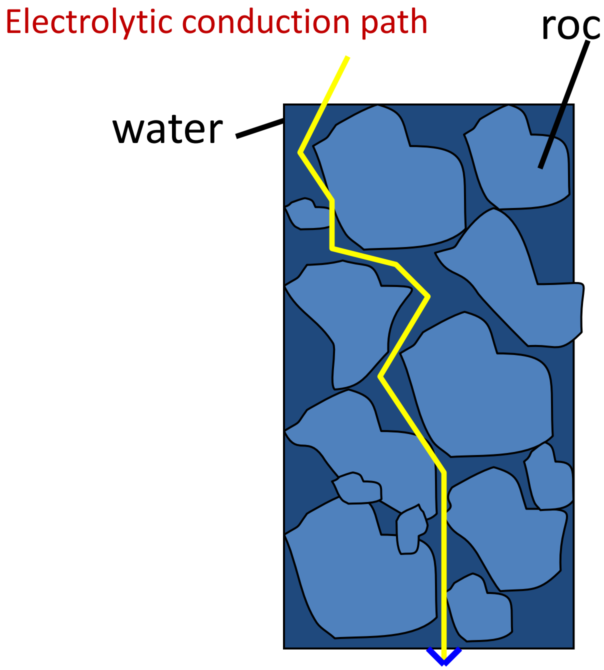
- An earth material typically contains three phases:

rock **non-conducting (?)**

water (with dissolved ions) **conducting**

air **non-conducting**

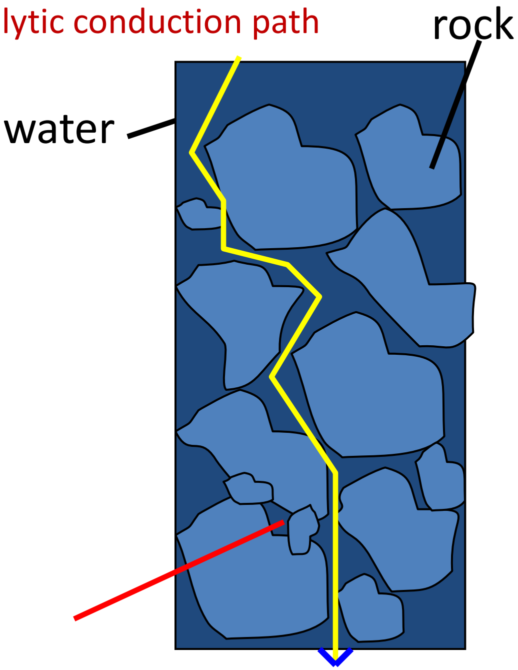
$$F = \frac{\sigma_w}{\sigma_{earth}} = \frac{\rho_{earth}}{\rho_w}$$



Presence of rock reduces conductivity relative to single phase electrolyte: this reduction in conductivity is characterized by the Formation Factor (F)

Case 1: What does F depend upon?

- Formation Factor (F) is related to physical properties of medium:



[a] Volume of conducting electrolyte relative to volume of rock or total volume

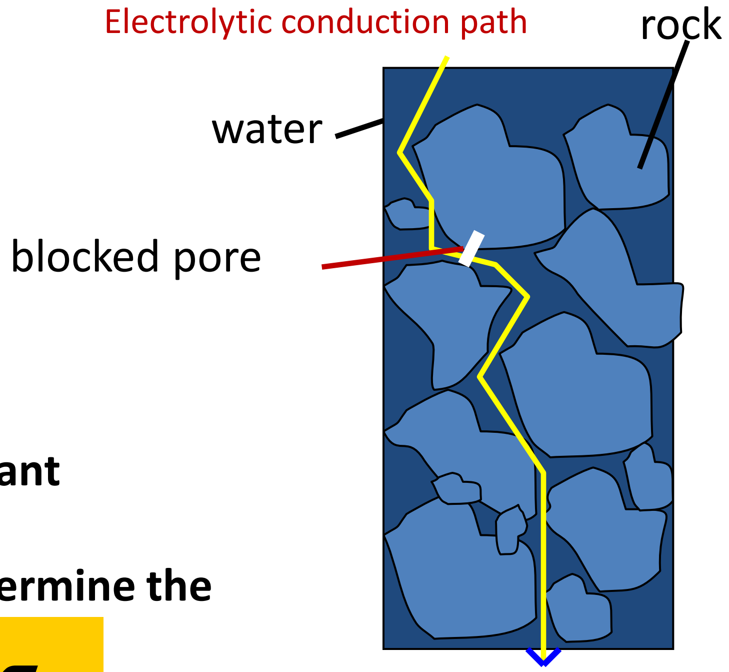
but it is only the <u>connected</u> pore volume that counts

[dead end pore space does not count]

Interconnected porosity (ϕ_{eff}) = $\dfrac{\text{Volume of interconnected pore space}}{\text{Total volume}}$

Case 1: What does F depend upon?

- Formation Factor (F) is related to physical properties of medium:



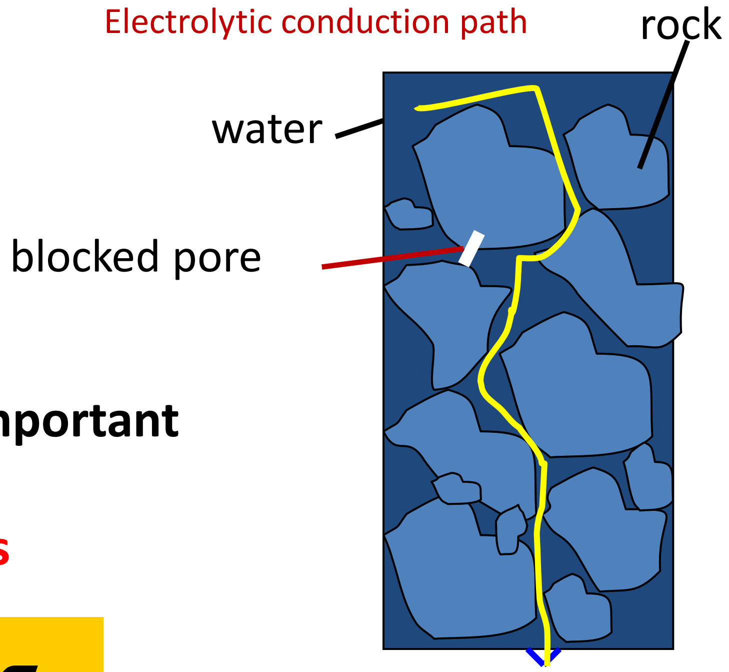
Tortuosity of ion transfer pathway is also important

Cementation or blocks in the pore space can determine the least resistive current flow path

$$F = \frac{\tau}{\phi_{eff}}$$

Case 1: What does F depend upon?

- Formation Factor (F) is related to physical properties of medium:



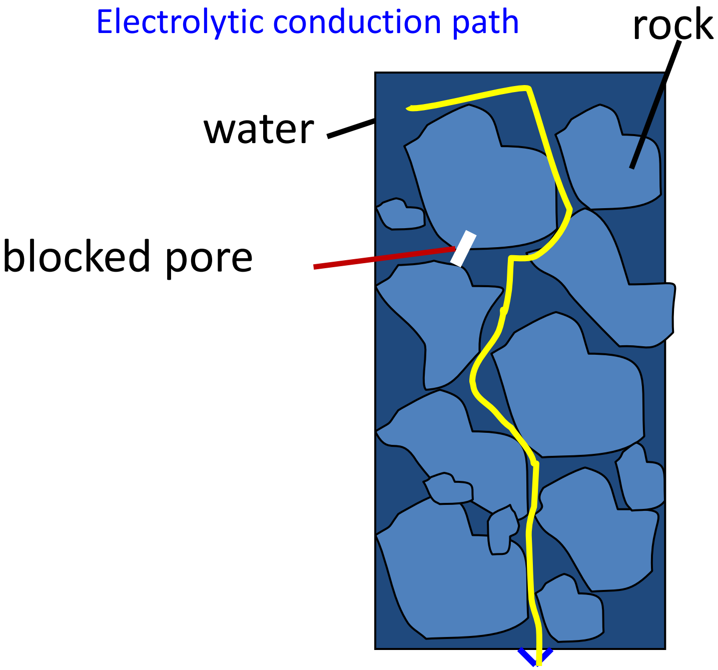
Tortuosity of ion transfer pathway is also important

The new current flow path is more tortuous

$$F = \frac{\tau}{\phi_{eff}}$$

Case 1: Only electrolytic conduction

- Archie's Law (1942) for saturated sediments:



$$\sigma_{earth} = \frac{1}{\rho_{earth}} = \frac{1}{F}\sigma_w = \sigma_w \phi_{eff}^m$$

m **is some indicator of the tortuosity of the pore space**

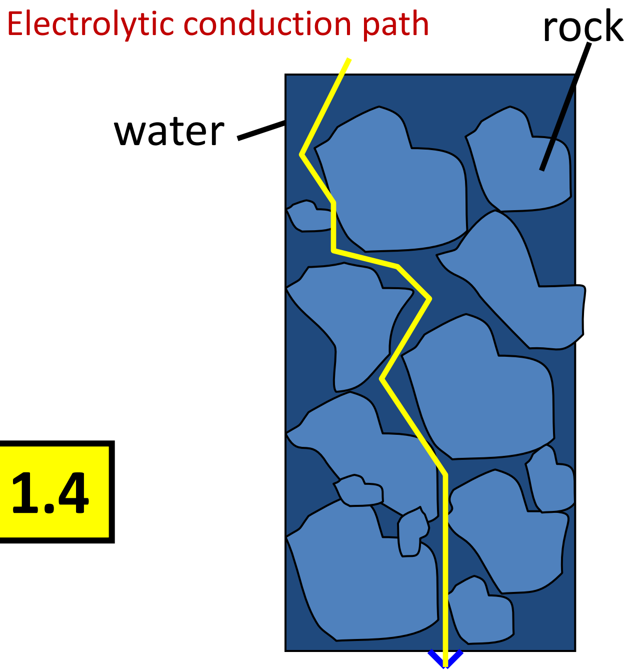
An empirical law based on observations - also theoretically derived (Sen, 1981)

Case 1: Only electrolytic conduction

- Archie's Law (1942) for saturated sediments:

$$\boxed{\sigma_{earth} = \frac{1}{\rho_{earth}} = \frac{1}{F}\sigma_w = \sigma_w \phi_{eff}^m}$$

m = 1.4

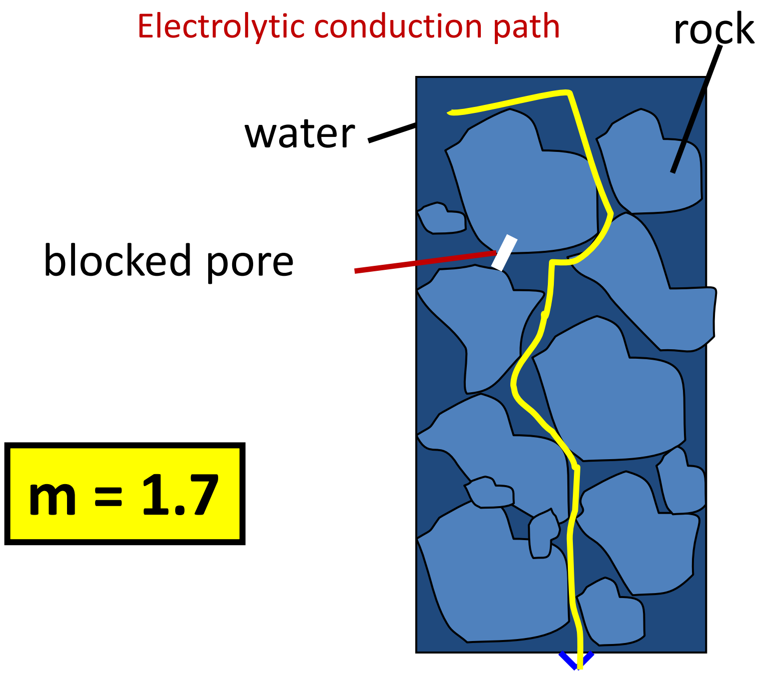


***m* is some indicator of the tortuosity of the pore space**

An empirical law based on observations - also theoretically derived (Sen, 1981)

Case 1: Only electrolytic conduction

- Archie's Law (1942) for saturated sediments:



$$\sigma_{earth} = \frac{1}{\rho_{earth}} = \frac{1}{F}\sigma_w = \sigma_w \phi_{eff}^m$$

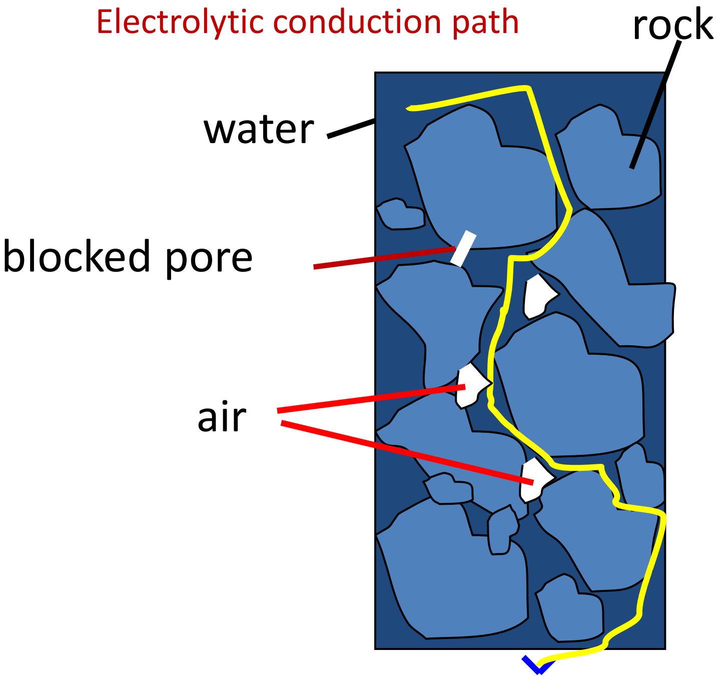
m = 1.7

***m* is some indicator of the tortuosity of the pore space**

An empirical law based on observations - also theoretically derived (Sen, 1981)

Case 1: Only electrolytic conduction

- Archie's Law (1942) for **un**saturated sediments:



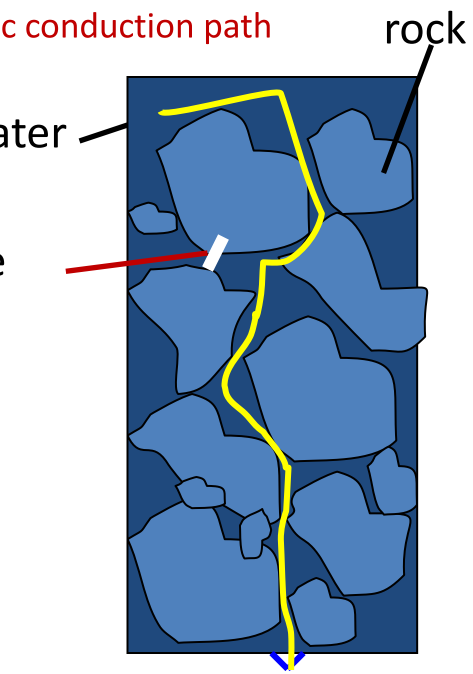
Air acts to increase the formation factor (*F*) by (1) reducing electrolyte volume (2) increasing tortuosity

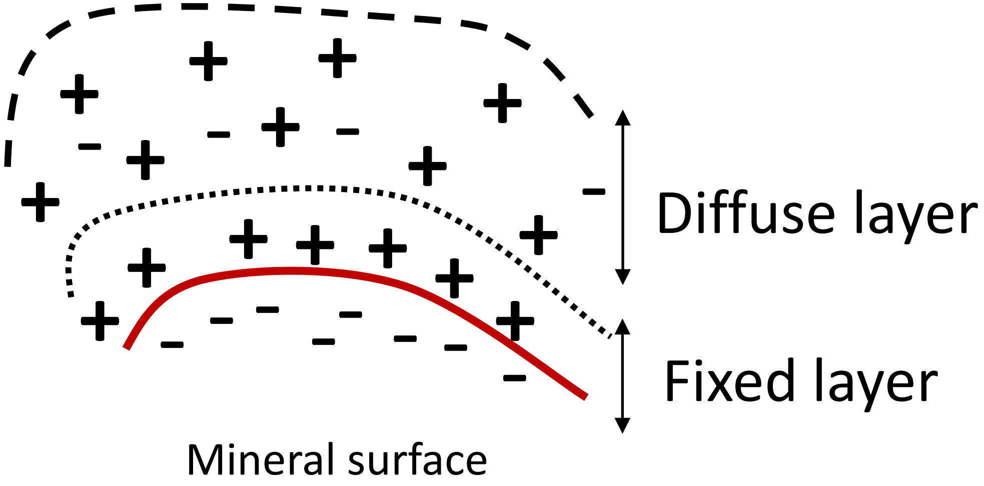
$$\boxed{\sigma_{earth} = \frac{1}{\rho_{earth}} = \frac{1}{F}\sigma_w = \sigma_w \phi_{eff}^m S_w^n}$$

***S_w* is the degree of saturation**
***n* is related to the rock type and distribution of air in pore space**

But is the rock really non-conducting?

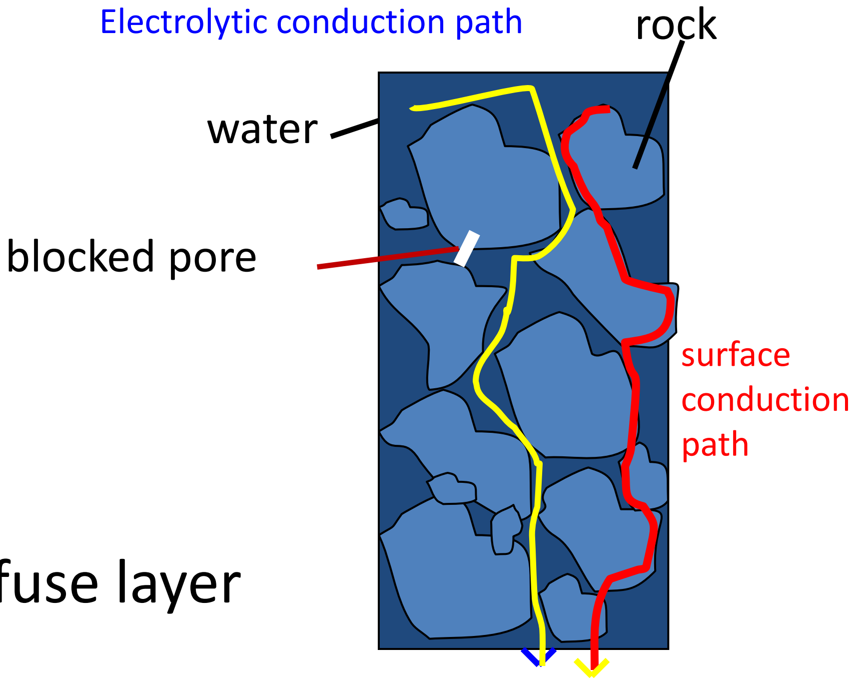
- A mineral surface typically contains a net negative charge which attracts net cations

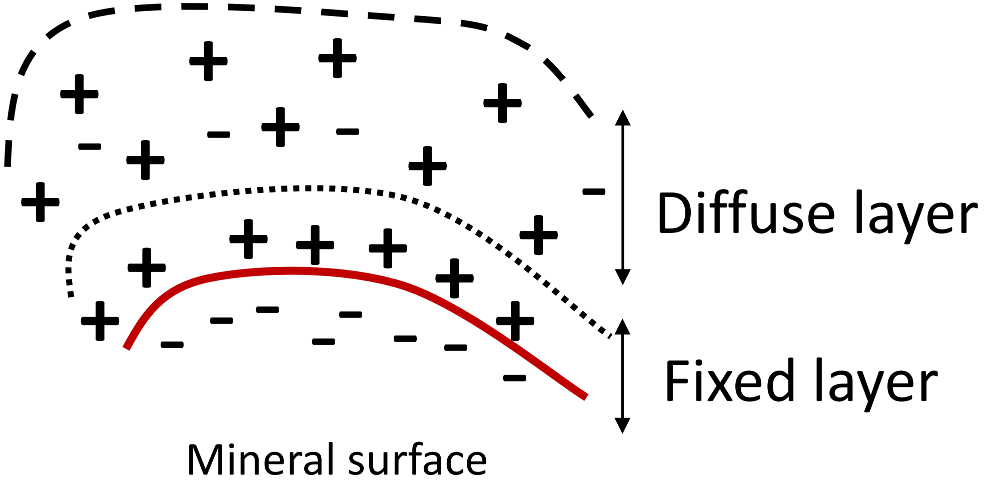




Surface conduction

- Now have two current conduction paths





Modification for surface conduction

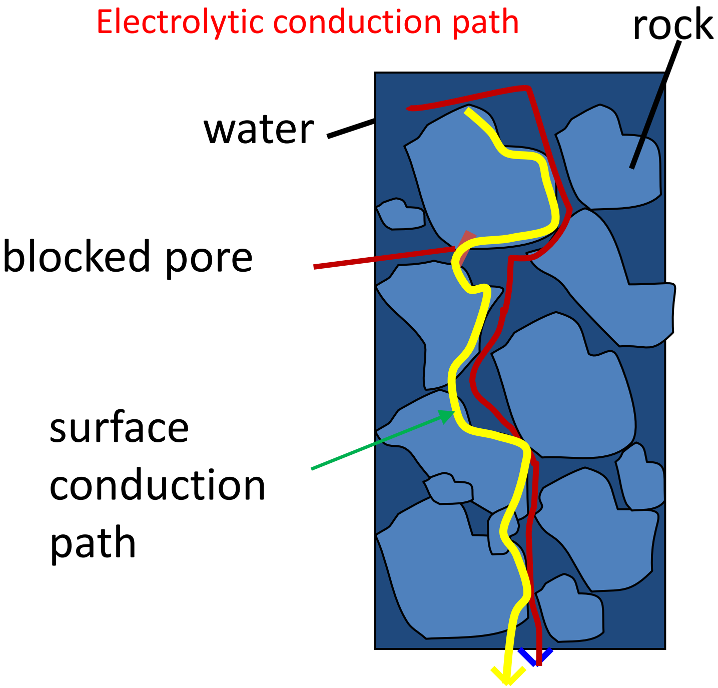
- Need modification of Archie's Law (Waxman & Smits, 1968):

Electrolytic & surface conduction paths are the same?

$$\sigma_{earth} = \frac{1}{\rho_{earth}} = \frac{1}{F}\sigma_w + \sigma_{surf}$$

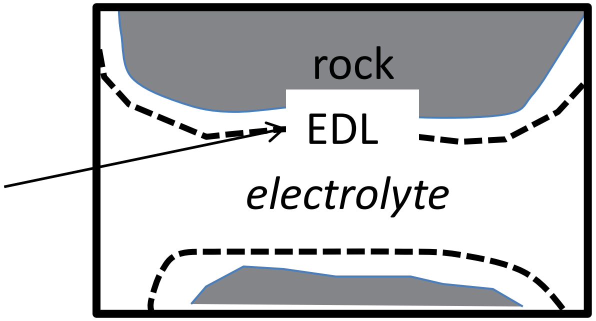
electrolytic conduction

surface conduction



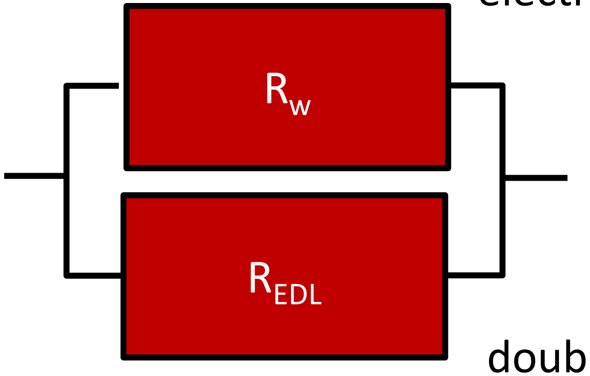
[assumes that conduction pathways add in parallel]

Parallel electrolytic and surface conduction terms



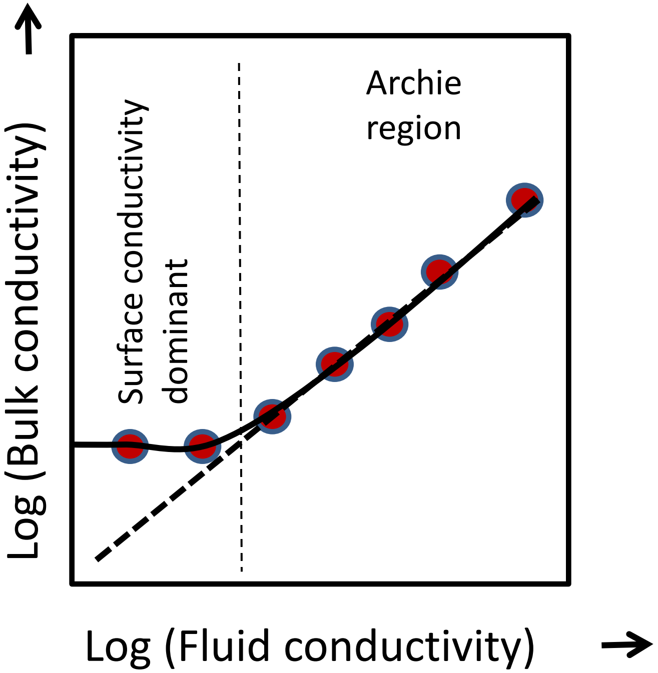
Electrical double layer

resistors in parallel



electrolyte

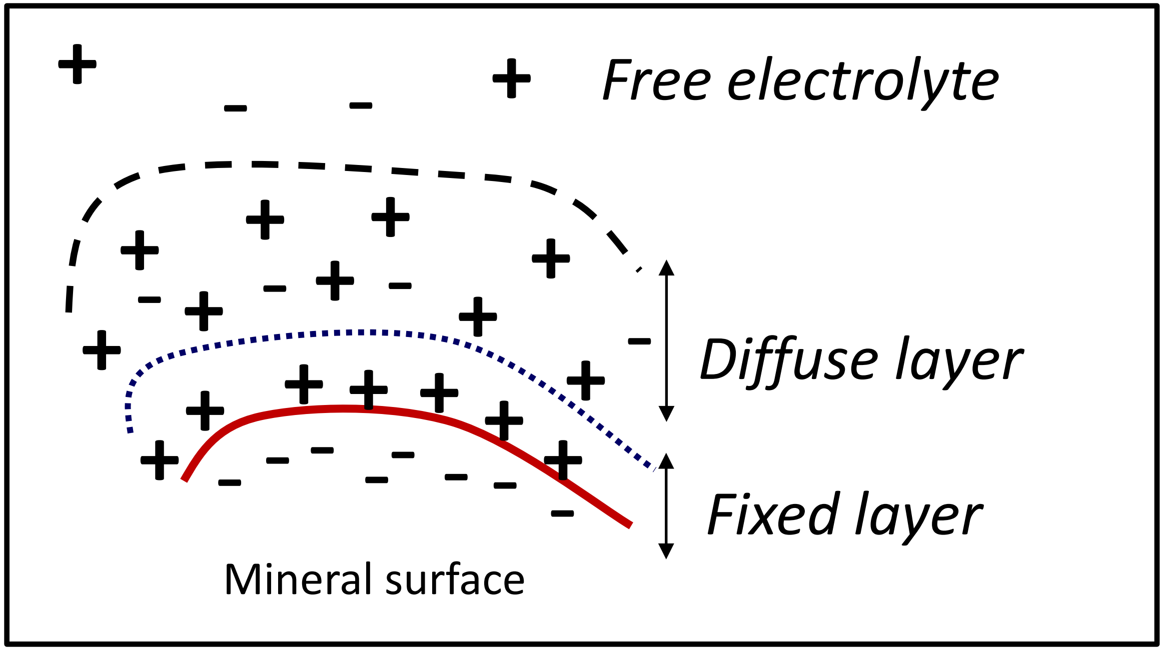
double layer



What is surface conduction dependent on?

- Complex and area of active research.

- Surface area available to hold charge
- Density of charges in double layer
- Mobility of ions in double layer

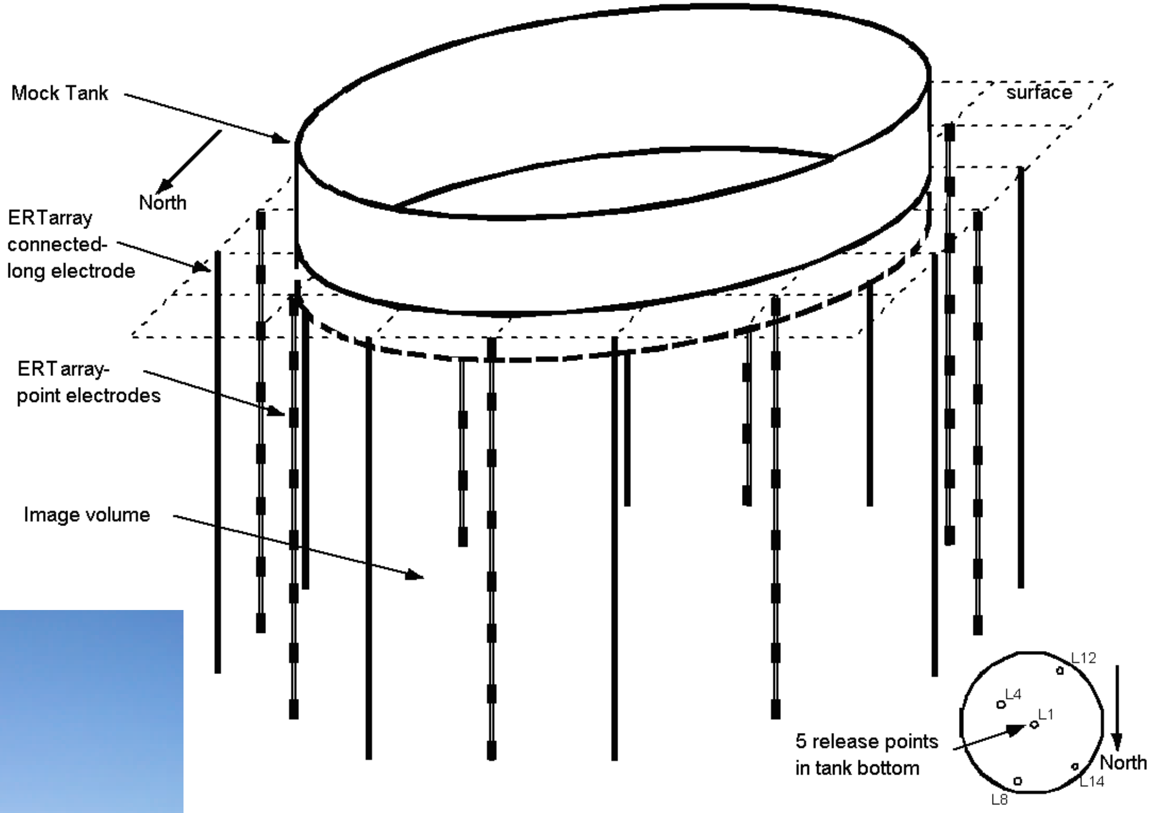


Examples of leak detection using electrical geophysics

Andrew Binley
Lancaster University

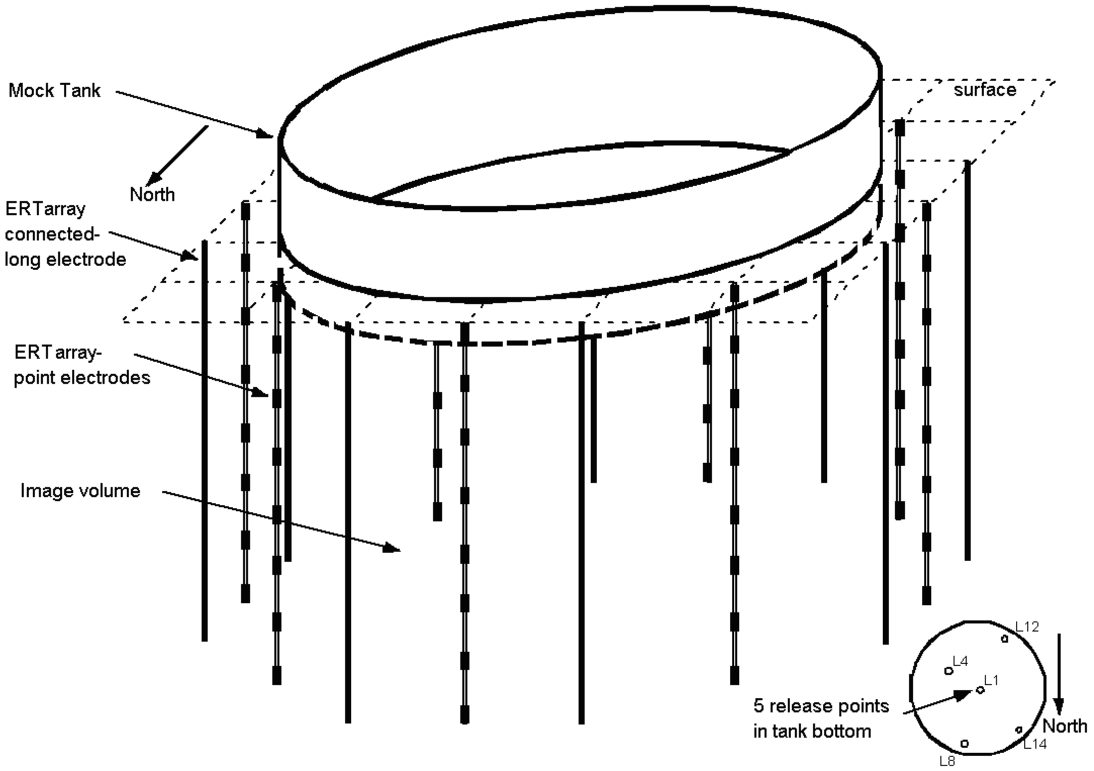
email: a.binley@lancaster.ac.uk

Imaging leaks using ERT – Hanford UST



Imaging leaks using ERT – Hanford UST

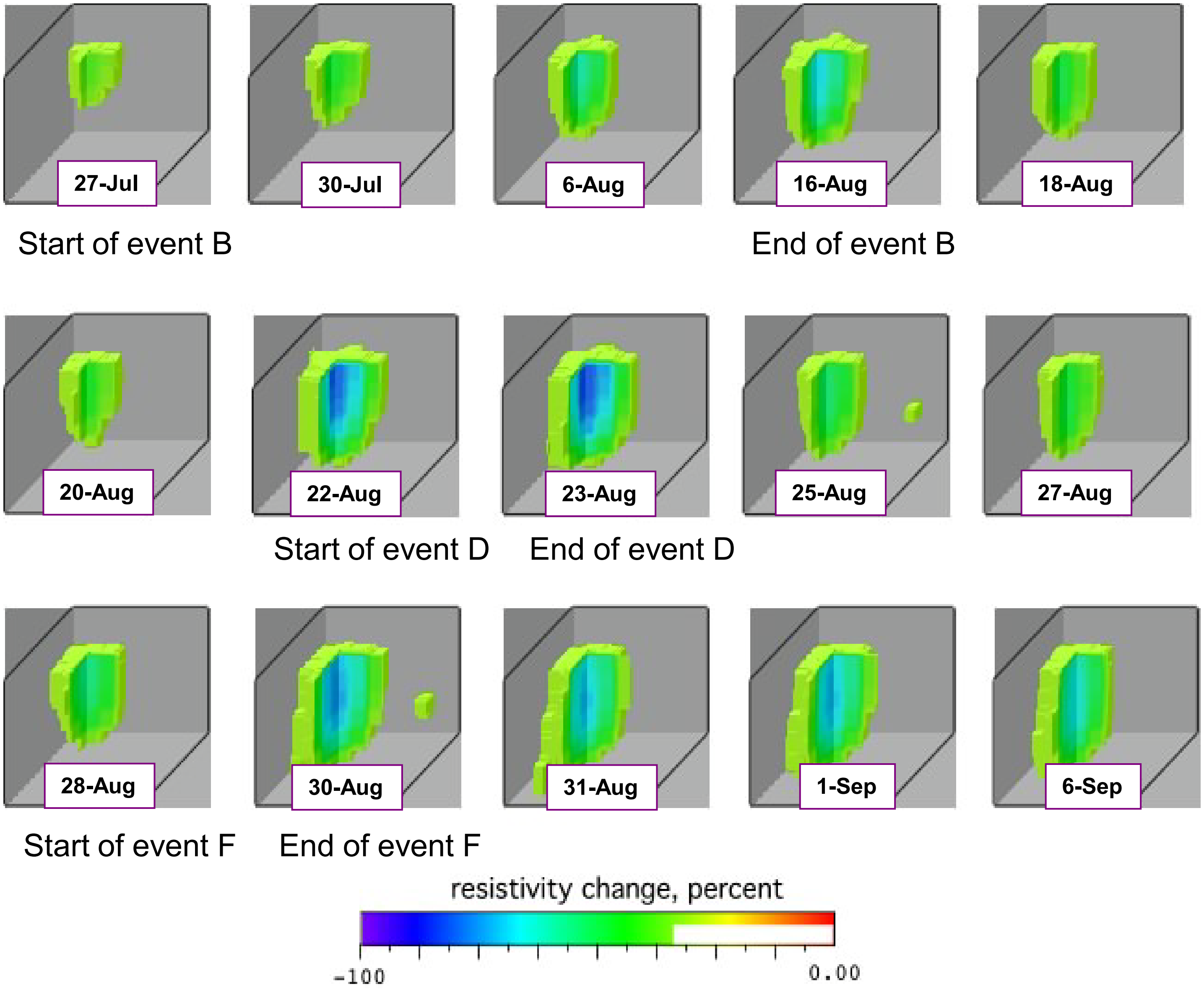
Ramirez et al.(1996) documented first trials of 3D ERT for imaging leaks from underground storage tanks at Hanford, using the 10.7m diameter “mock tank facility”.



In 2003 a “blind trial” was conducted and reported in Daily et al.(2004). A total of 54 m^3 of sodium thiosulfate was leaked from a number of locations over a period of 110 days.

Daily et al. collected data each day (remotely), process data and inform the operators if leaks existed.

Imaging leaks using ERT – Hanford UST



Start of event B

End of event B

Start of event D

End of event D

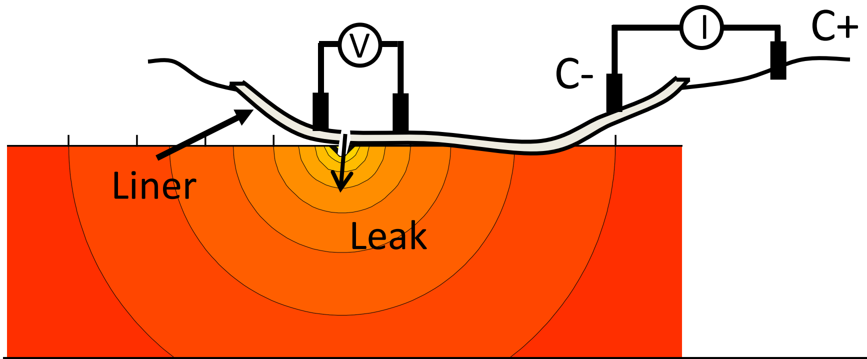
Start of event F

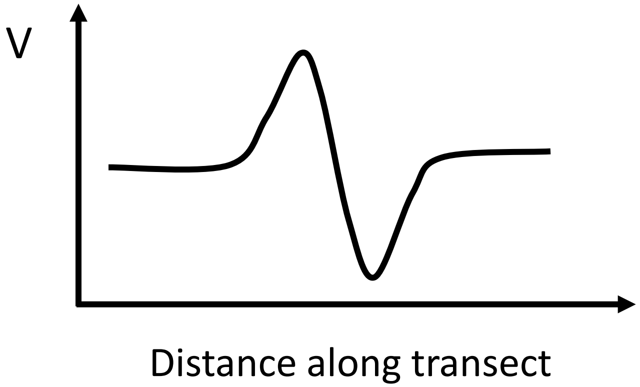
End of event F

Daily, Ramirez and Binley (2004)

Leak location using electrical current sources

Binley et al.(1997) proposed an alternative approach in which electrical leaks were created along the hydraulic leaks and the location of these leaks then determined.

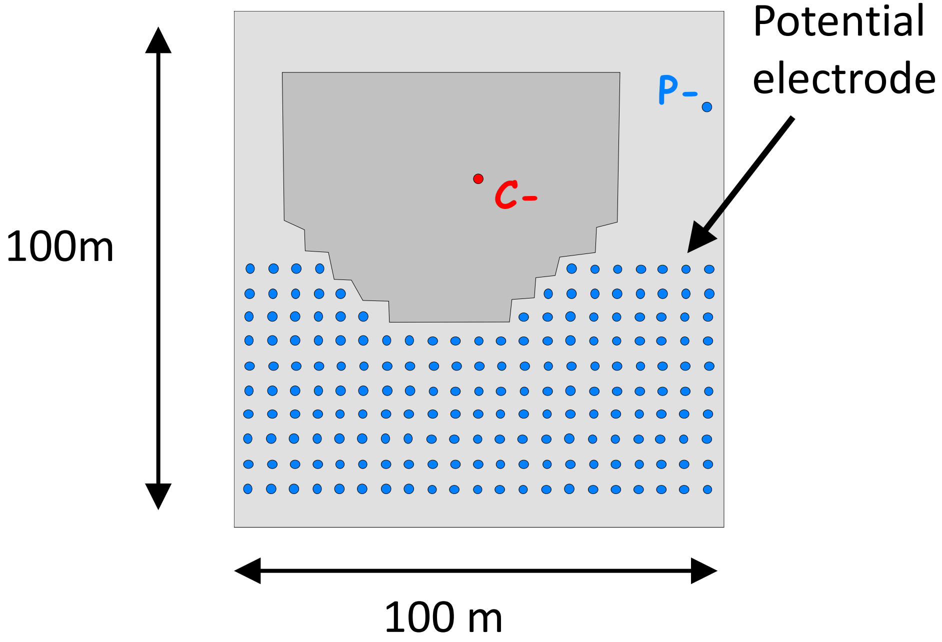


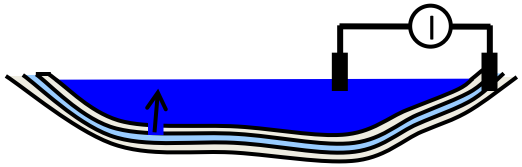


Binley, Daily and Ramirez (1997)

Leak location using electrical current sources

Success of the method has been demonstrated

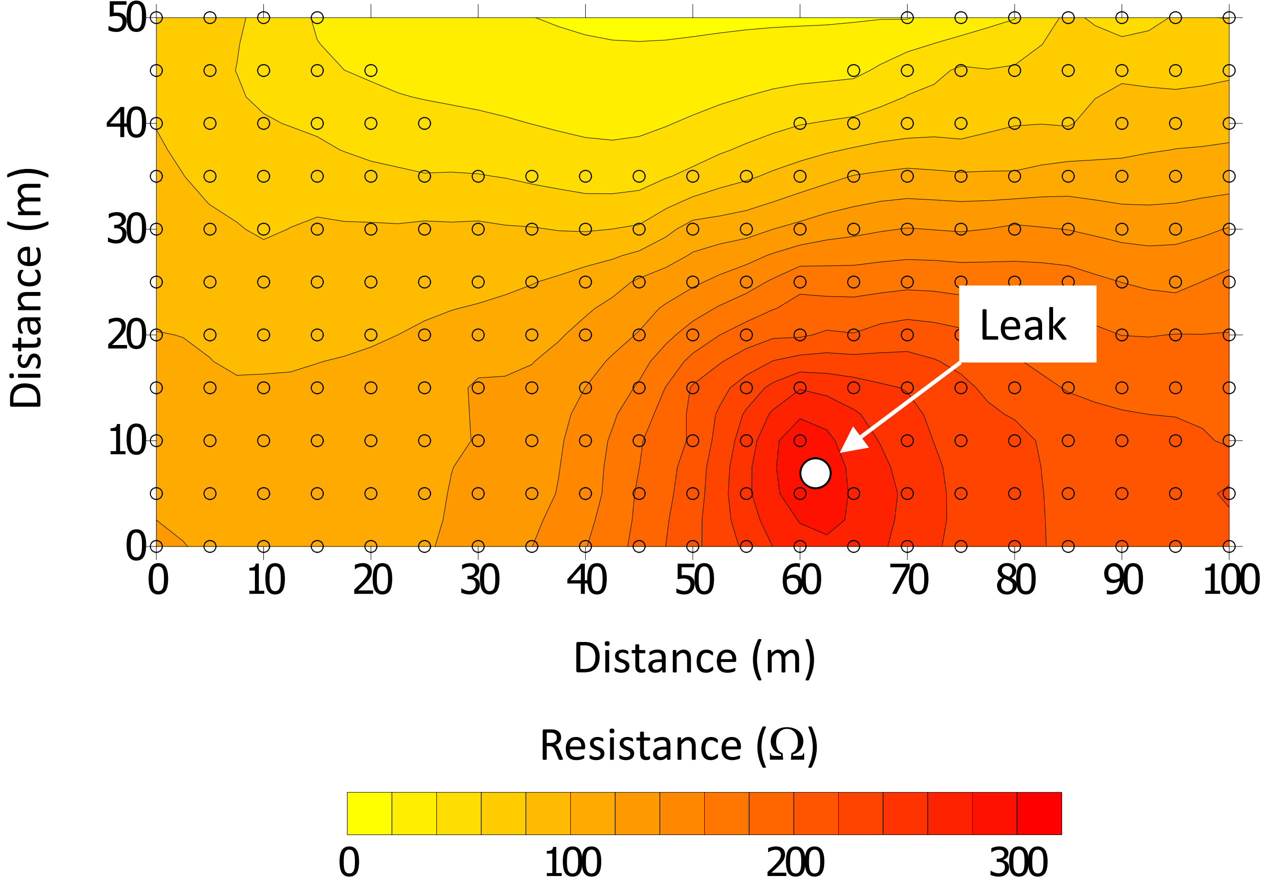




C+ electrode installed in between liners of double liner

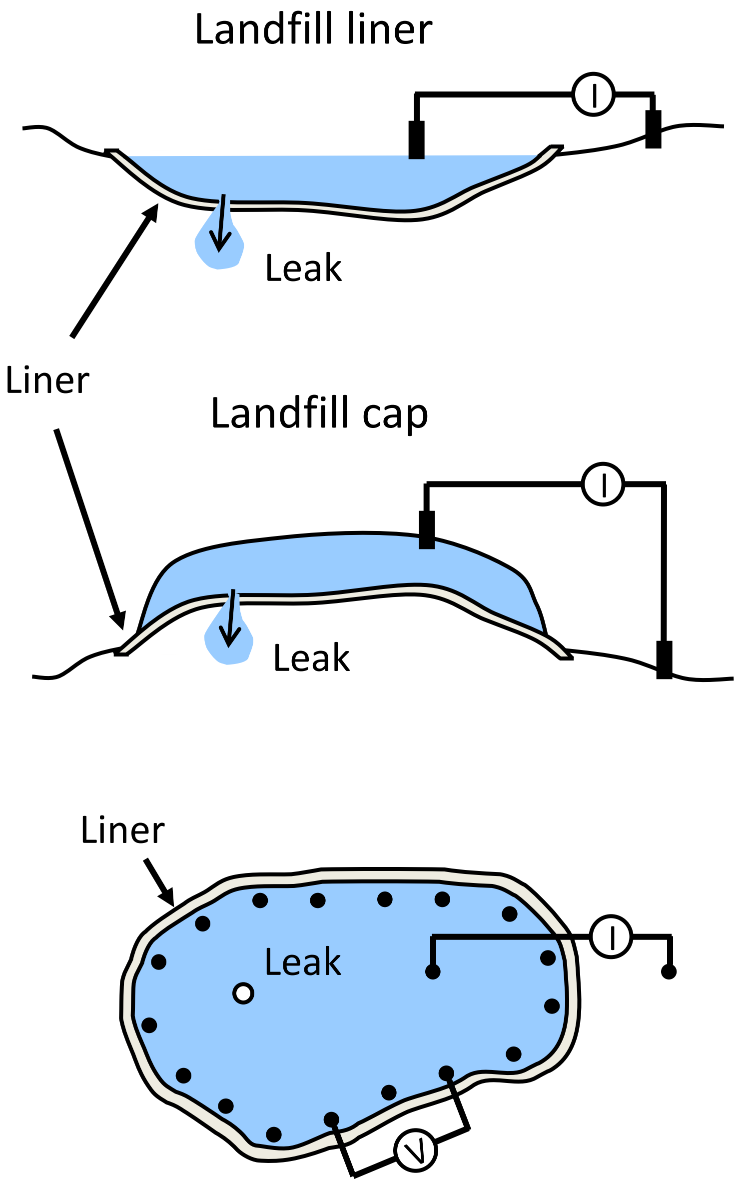
Leak location using electrical current sources

Just mapping potentials associated with current source due to a leak in a membrane



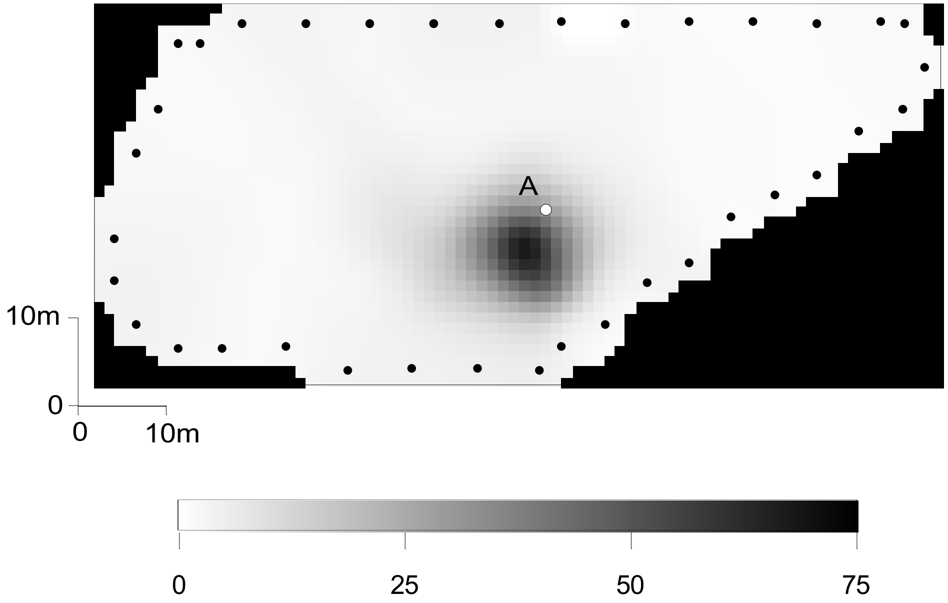
Laine, Binley and Darilek (1997)

Leak location using electrical current sources



In cases where access inside or underneath the storage facility is not possible then we can used perimeter electrodes and determine, using inverse methods, the location of the current sources (leaks)

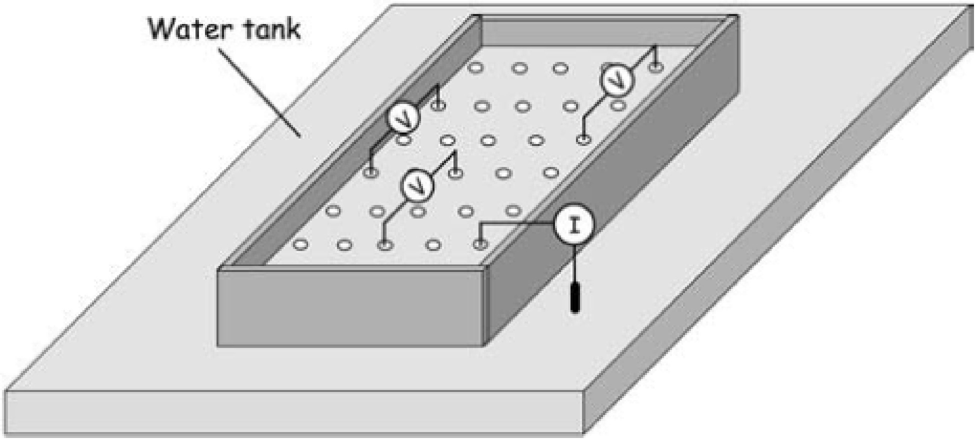
Site 300, Livermore

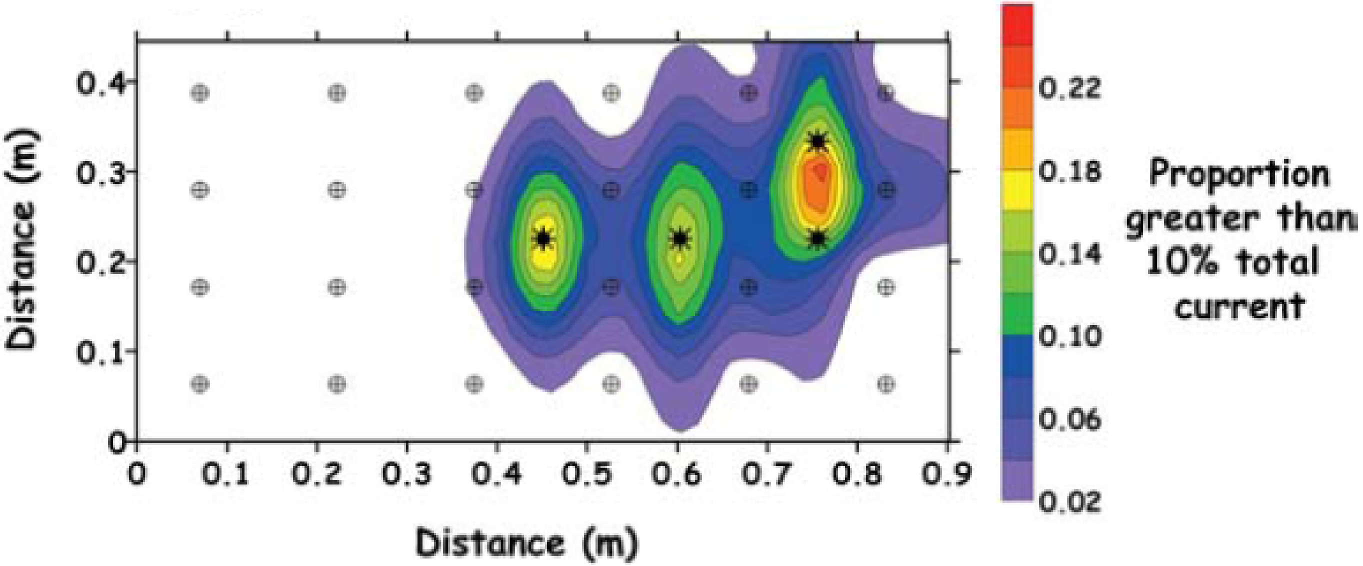


Binley, Daily and Ramirez (1997)

Leak location using electrical current sources

Using data from a laboratory model, Binley and Daily (2003) examined the sensitivity of the method, in particular the number of concurrent leaks that could be resolved.

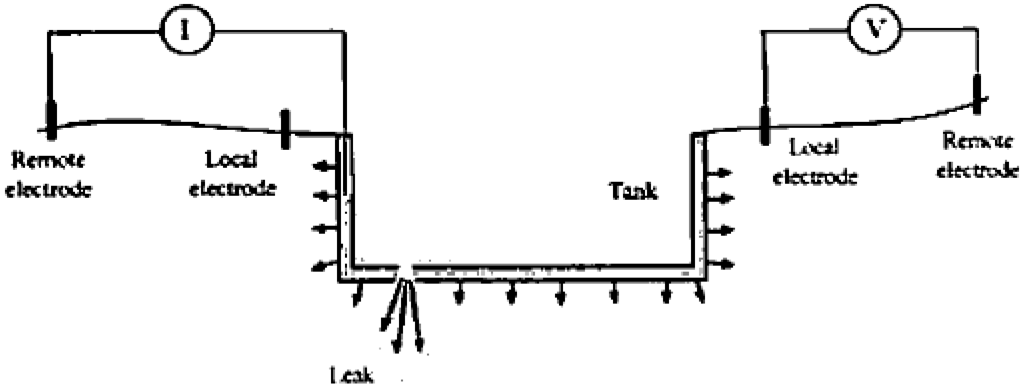




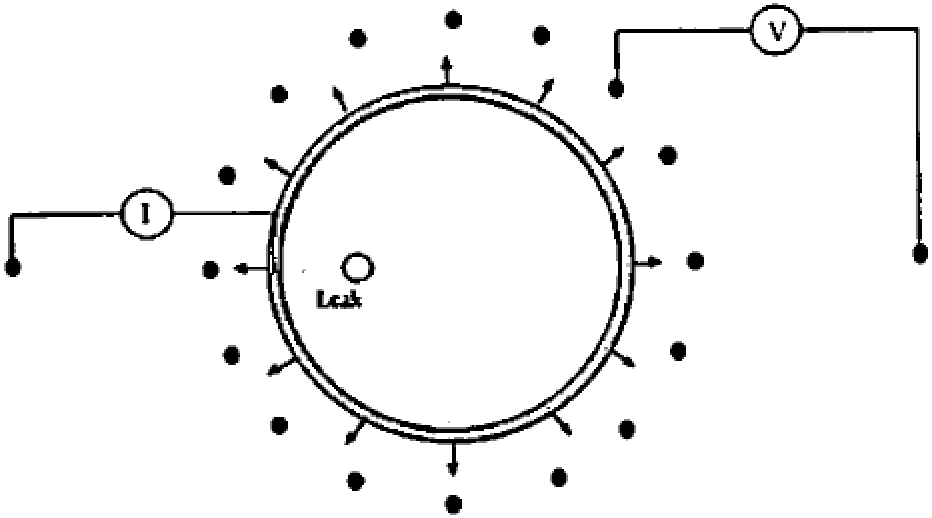
Binley and Daily (2003)

Leak location using electrical current sources

Binley at al.(1997) also demonstrated that the same approach can be used for electrically conductive storage facilities, e.g. metal storage tanks.



Vertical Section



Further reading

Binley, A. and W. Daily, 2003, The performance of electrical methods for assessing the integrity of geomembrane liners in landfill caps and waste storage ponds, Journal of Environmental and Engineering Geophysics, 8(4), 227-237.

Binley, A., W. Daily and A. Ramirez, 1997, Detecting Leaks from Environmental Barriers using Electrical Current Imaging, Journal of Environmental and Engineering Geophysics, 2.(1), p11-19.

Daily, W., A. Ramirez and A. Binley, 2004, Remote Monitoring of Leaks in Storage Tanks using Electrical Resistance Tomography: Application at the Hanford Site, Journal of Environmental and Engineering Geophysics, 9(1), 11-24.

Laine, D.L., A.M. Binley and G.T. Darilek, 1997, How to Locate Liner Leaks Under Waste, Geotechnical Fabrics Report, Vol. 15(6), p34-36, 1997.

Laine, D.L., G.T. Darilek and A.M. Binley, 1997, Locating Geomembrane Liner Leaks under Waste in a Landfill, In: Proceedings of the International Geosynthetics '97 Conference, Long Beach, CA, USA, Industrial Fabrics Association International, Saint Paul, Minnesota, Vol. 1, p407-411.

Ramirez, A., W. Daily, A. Binley, D. LaBrecque and D. Roelant, 1996, Detection of Leaks in Underground Storage Tanks Using Electrical Resistance Methods, Journal of Environmental and Engineering Geophysics, 1 (3), 189-203.

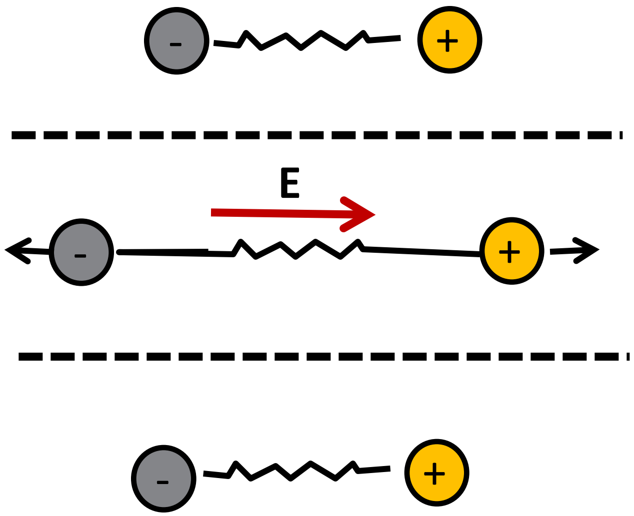
EXTRA MATERIAL

Interpretation of ground penetrating radar (GPR) measurements

2.2. HIGH FREQUENCY ELECTRICAL PROPERTIES

Displacement Currents

- Storage of Energy



No E Field

E Field

E Field removed

$$J = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

dielectric permittivity

Usually the dominant mode of charge transfer at high frequencies used in GPR

Electromagnetic wave velocities

- Written as function of physical properties:
- Permittivity, ε
- Conductivity, σ
- Permeability, μ

$\varepsilon_r = \varepsilon/\varepsilon_0$ (1-80)
$\mu_r = \mu/\mu_0 \approx 1$
$\sigma \approx 0.0001\text{-}10$ S/m

ε_o = permittivity of free space (8.854×10^{-12} F/m)
$\mu_0 = 4\pi.10^{-7}$ H/m

Controlling factors on velocity of radar wave:

The full expression:

P = loss factor

c = 0.3 m/ns

ε_r = relative dielectric constant

μ_r = relative magnetic permeability

ε_o = permittivity of free space (8.854×10^{-12} F/m)

σ = conductivity

f = frequency in Hz

$$V = \frac{c}{\left\{ \frac{\varepsilon_r \mu_r}{2} \left[\left(1 + P^2 \right) + 1 \right] \right\}^{1/2}}$$

$$P = \frac{\sigma}{\omega \varepsilon}$$

$$\varepsilon = \varepsilon_r \varepsilon_o$$

$$\omega = 2\pi f$$

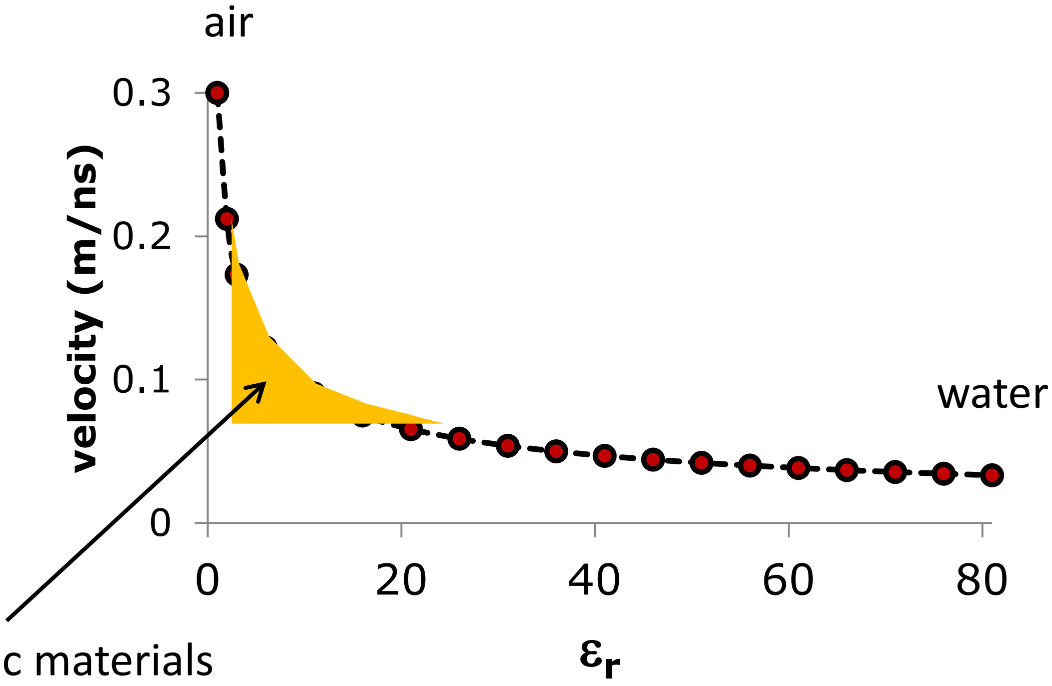
In low loss materials (P ≅ 0) often assumed:

$$V = \frac{c}{\sqrt{\varepsilon_r}} = \frac{0.3}{\sqrt{\varepsilon_r}} (m/ns)$$

Relationship between permittivity and velocity

- Large range of radar wave velocities encountered in earth
- Importance in interpretation - depth estimation

$$V = \frac{c}{\sqrt{\varepsilon_r}} = \frac{0.3}{\sqrt{\varepsilon_r}} (m/ns)$$



most geologic materials

Relative dielectric constant for various geologic materials

- Ranges are guide figures - may not include extremes
- Dielectric constant of all materials is not resolved

Material	**ε_r**	**V (m/ns)**
Air	1	0.3
Fresh Water	81	0.03
Permafrost	4-5	0.15-0.13
Granite	4-9	0.15-0.10
Dry sand	4-10	0.15-0.09
Wet sand	10-20	0.09-0.07
Aviation gasoline	2	0.21

Topp equation

- Described by Topp et al, 1980
- The most popular empirical model for θ estimation
- Fits a third order-polynomial function to the observed permittivity response of sandy/loam soils as determined from TDR experiments
- Appropriate for frequencies in the 10MHz-1GHz range, as it agrees well with observed values over a wide range of water contents (~5-50%)

$$\varepsilon' = 3.03 + 9.3\theta_v + 146\left(\theta_v^2\right) - 76.6\left(\theta_v^3\right)$$

assuming low-loss material and $\varepsilon_s \approx 3\text{-}4$

Topp, G.C., J.L. Davis, and A.P. Annan. 1980, Electromagnetic determination of soil water content, Measurement in coaxial transmission lines. Water Resources Research 16(3):574-582.

Topp equation (cont.)

- Accurate result require selection of appropriate polynomial coefficients from an evaluation of experimental data (e.g. calibration)

$$\varepsilon' = a + b\theta_v + c\left(\theta_v^2\right) - d\left(\theta_v^3\right)$$

- Often considered inappropriate for clays and organic rich soils (Friedman, 1998)
- Other polynomial models exist (e.g. Curtis, 2001; Roth et al, 1990) very useful for water content estimation

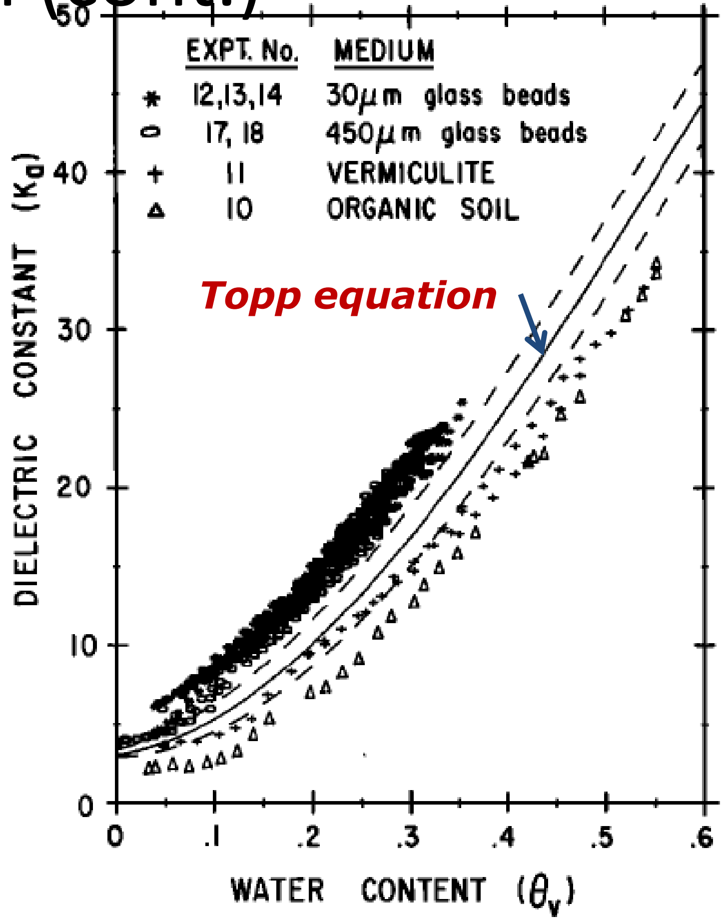
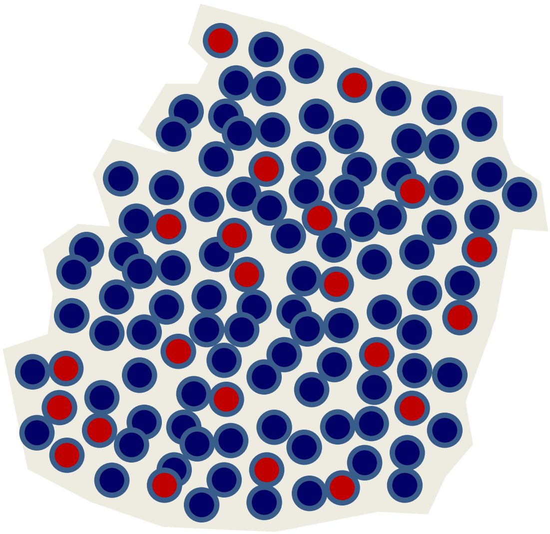
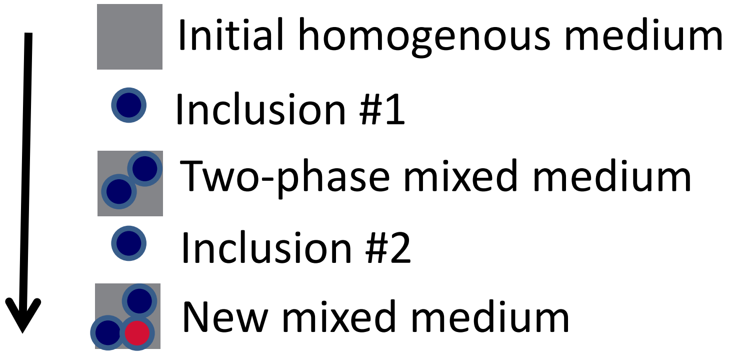


Fig. 6. The measured relationship between K_a and θ_v for the mineral soils, 30 μm glass beads, ground vermiculite, and an organic soil. The area between the dashed lines is the same region as between the dashed lines in Figure 4.

Topp et al., 1980, Water Resources Res.

Mixing models





Initial homogenous medium

Inclusion #1

Two-phase mixed medium

Inclusion #2

New mixed medium

- Mixing models to simulate bulk effective permittivity of a material <u>from knowledge of its component parts</u>
- Requires knowledge of matrix material, texture, effective surface area, grain shape, porosity, density, etc

Complex Refractive Index (CRIM) model

- Volumetric mixing model accounting for 3 phases

$$\varepsilon_{r(b)}^{\alpha} = \theta\varepsilon_{r(w)}^{\alpha} + (1-\phi)\varepsilon_{r(s)}^{\alpha} + (\phi-\theta)\varepsilon_{r(a)}^{\alpha}$$

bulk soil — water — solid soil matrix — air

ϕ = porosity
θ = moisture content

EM wave parallel to bedding α =1
EM wave perpendicular to bedding α = 0.5

Physical assumption: time for an EM wave to travel through a porous material is equal to the sum of the travel times for it to pass through the separate phases of the material (solid grains and pore water) – depending on geometric arrangement

CAN BE READILY MODIFIED TO INCLUDE A HYDROCARBON CONTAMINANT PHASE