



**RUTGERS**  
NEWARK

# **Soil Physics of Leak Detection using Geoelectrical Methods**

Lee Slater, Department of Earth & Environmental  
Sciences, Rutgers University, Newark

Contributing Author: Andrew Binley, School of Earth &  
Environmental Sciences, Lancaster University (UK)

LANCASTER  
UNIVERSITY



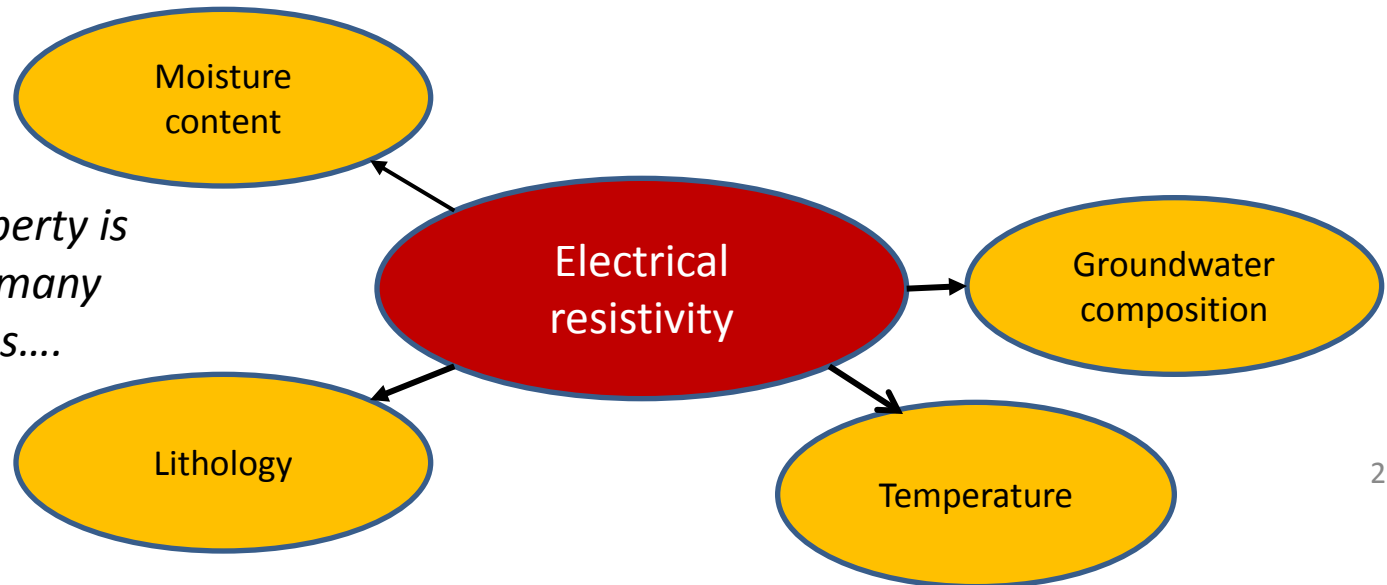
# What can geophysics really offer?

## PROS

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

## CONS

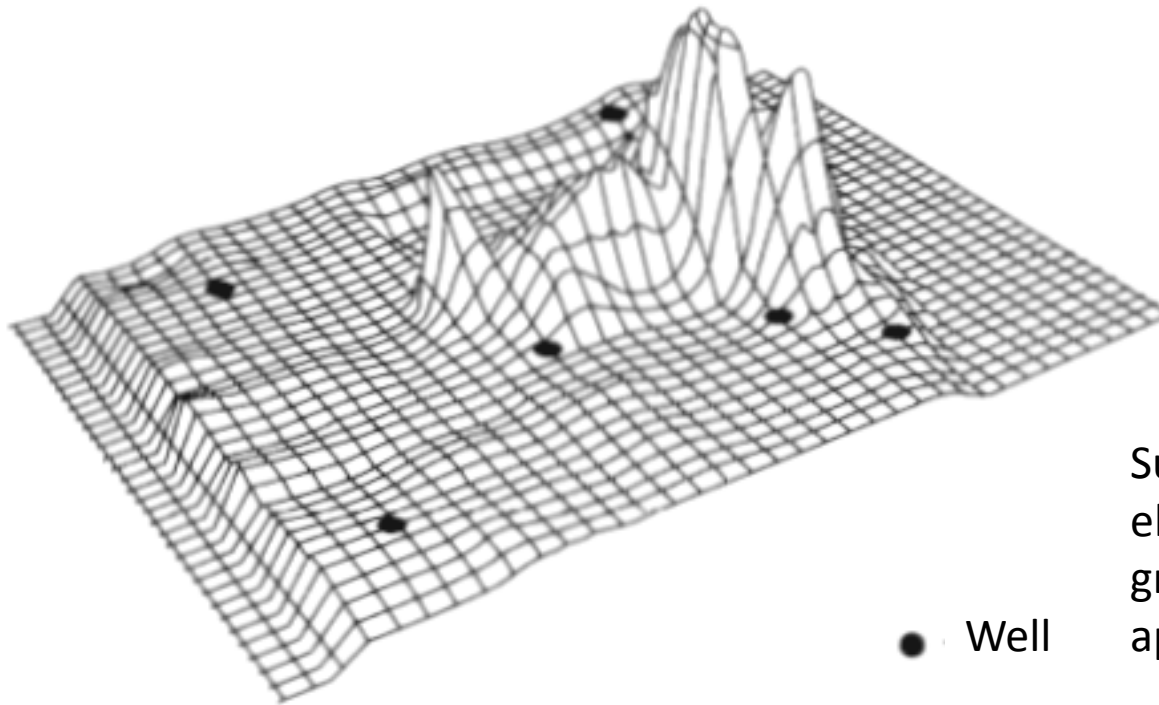
- **geophysical properties are an indirect function of the earth properties to be determined in site investigations**
- Highly sensitive to infrastructure



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

# 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.



● Well



*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**

Is there a strong

**DETECTING**

**BOTH**

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!!!**

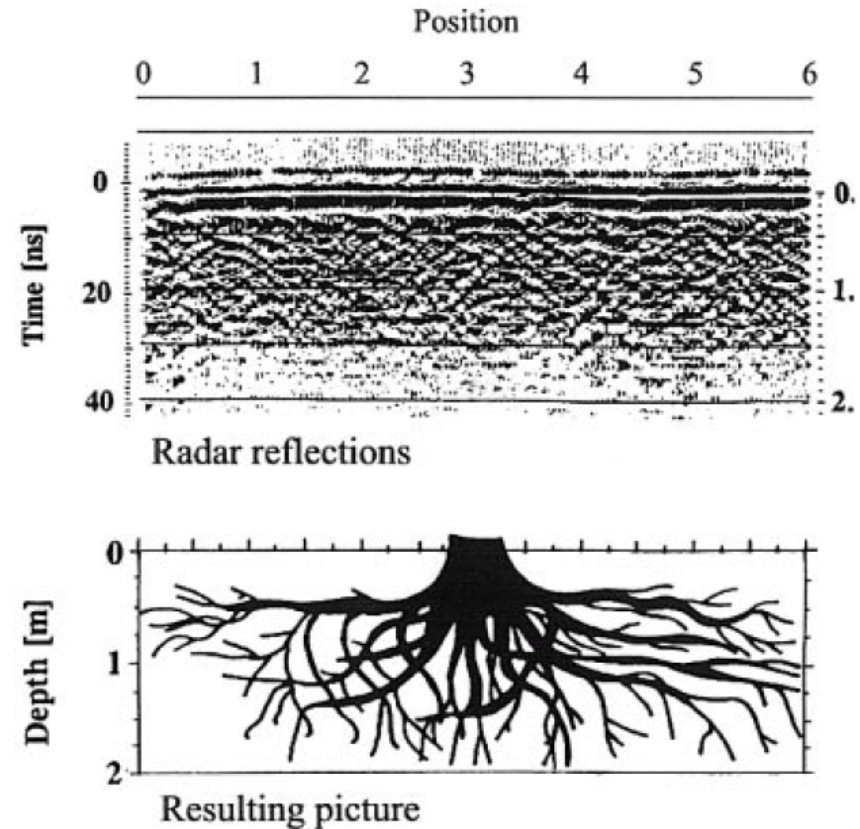


# Buyer beware of bad geophysics.....

There are many examples of bad geophysical survey practice and misinterpretation

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

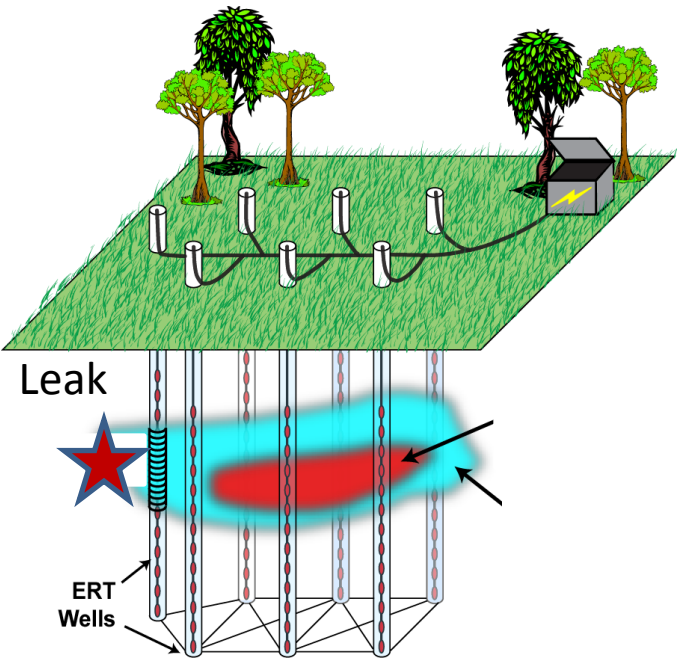
this interpretation is physically  
impossible



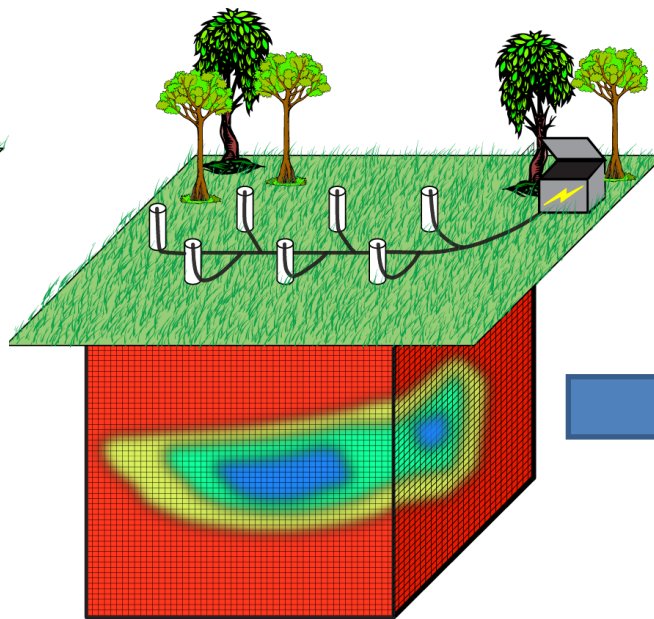
**Fig. 1.** Upper panel: an example of the primary radar image (radar reflections in the soil along a defined path across analysed roots), and lower panel: the resulting picture of the root system of large winter oak—*Quercus petraea* (Mattusch) Liebl. (modified after Hruška *et al.*, 1999).

# How much information do you need?

GEOPHYSICAL SURVEY OVER LEAK LOCATION



GEOPHYSICAL IMAGE OF LEAK DISTRIBUTION?

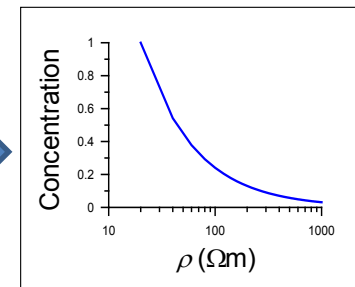


Qualitative information

ESTIMATES OF CONTAMINANT CONCENTRATION?

very uncertain!

PETROPHYSICAL TRANSFORM



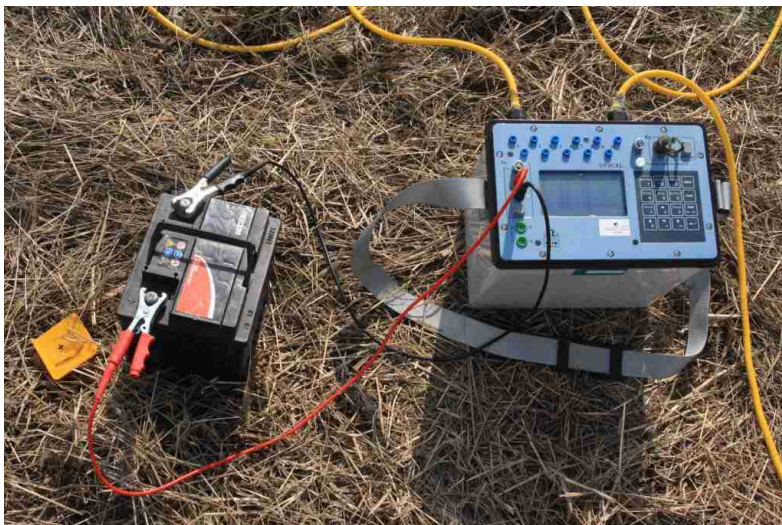
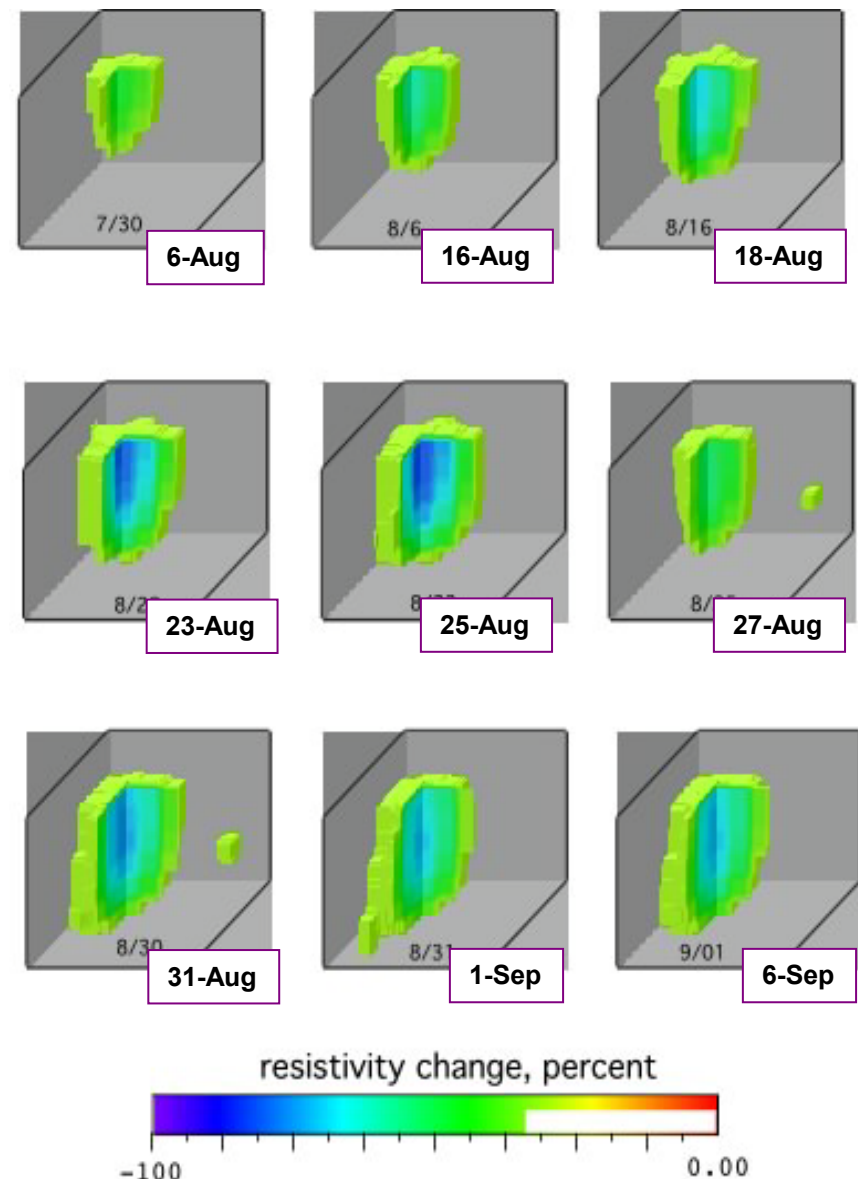
Quantitative information

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

# 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<sup>3</sup> of sodium thiosulfate was leaked from a number of locations over a period of 110 days.*

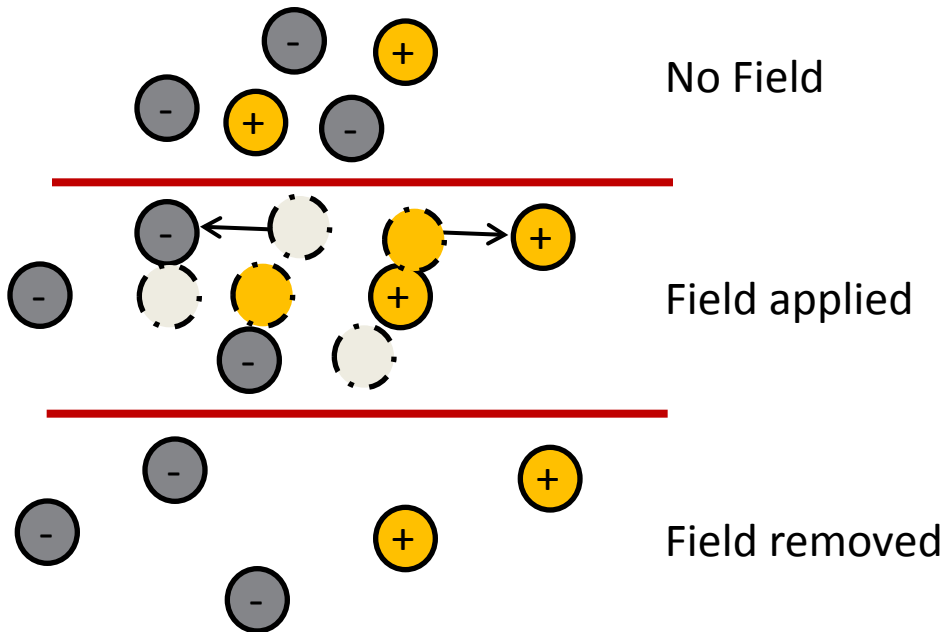
# **RESISTIVITY PETROPHYSICS BASICS**

# Conduction Currents

Current density

Electric field

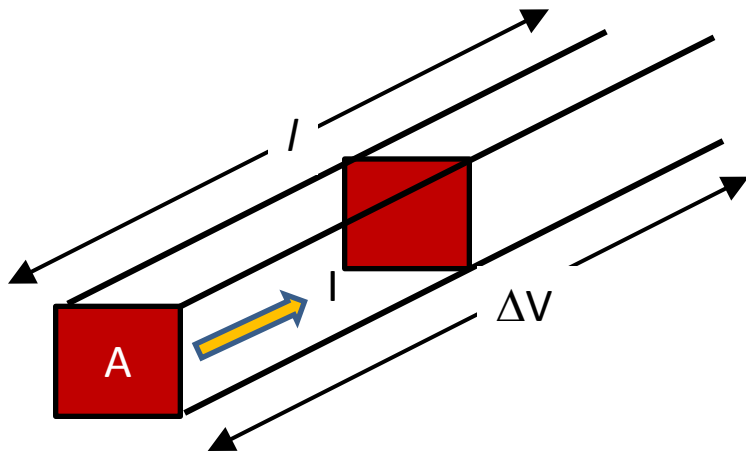
$$\mathbf{J} = \sigma \mathbf{E}$$



$\sigma$  = electrical conductivity:  
*a measure of a material's ability to  
conduct an electric current*

# Electrical resistivity ( $\rho$ )

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

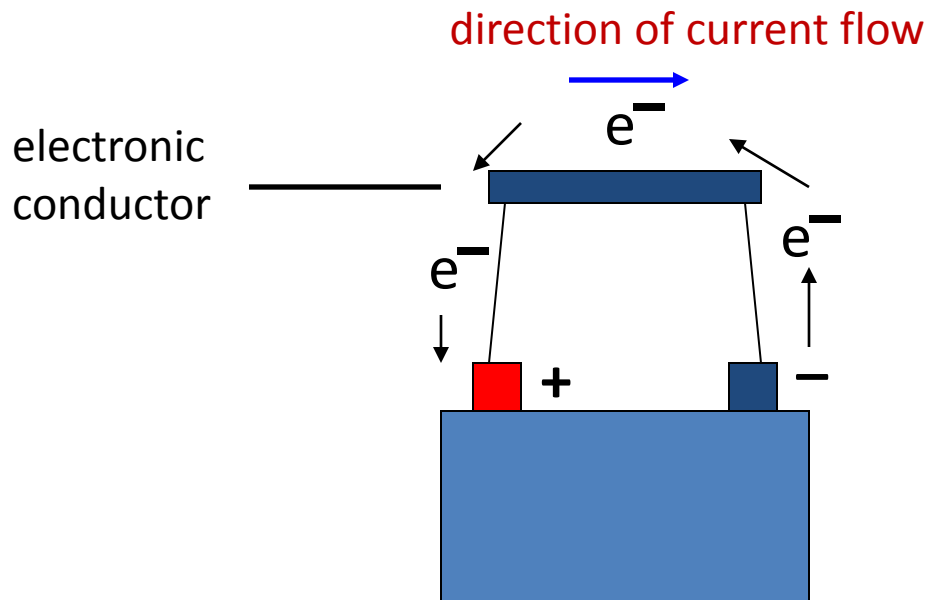
*RESISTANCE UNITS: volt/ampere = Ohms*

*RESISTIVITY UNITS: Ohm m*

# How does electrical current flow?

- Electrical current:  
Movement of charge

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

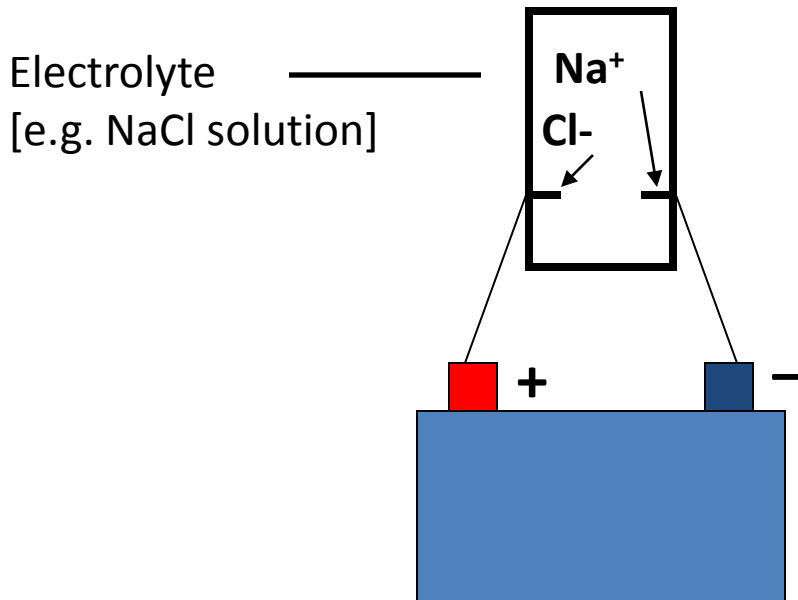


# How does electrical current flow **in the earth**?

- Electrolytic (water)



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

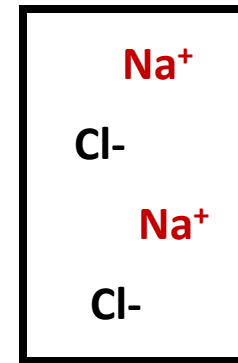




# Electrical conductivity

- **Conductivity ( $\sigma$ )**: the ability of a material to conduct electric current
- **Resistivity ( $\rho$ )**: the reciprocal of conductivity

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



NaCl solution - able to conduct



Vacuum - unable to conduct

Conductivity of electrolyte ( $\sigma_w$ ) increases with ionic concentration

# Case 1: Only electrolytic conduction

- An earth material typically contains three phases:

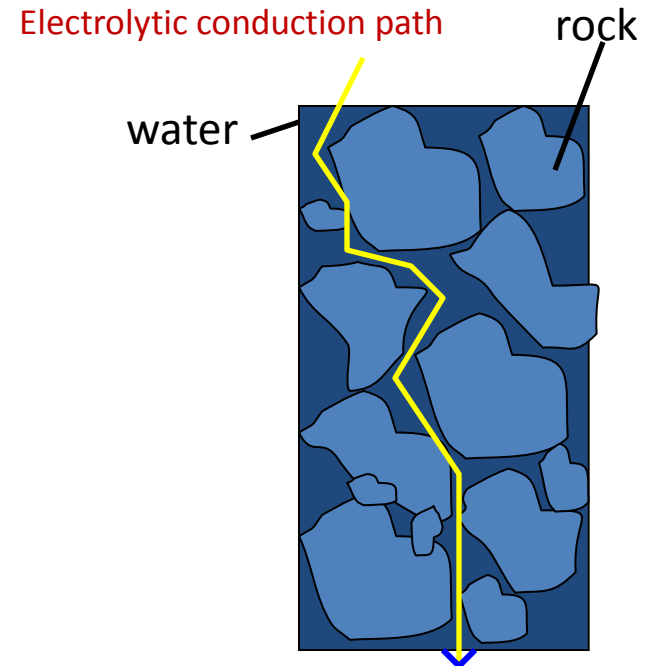
rock non-conducting (?)

water (with dissolved ions)

air non-conducting

conducting

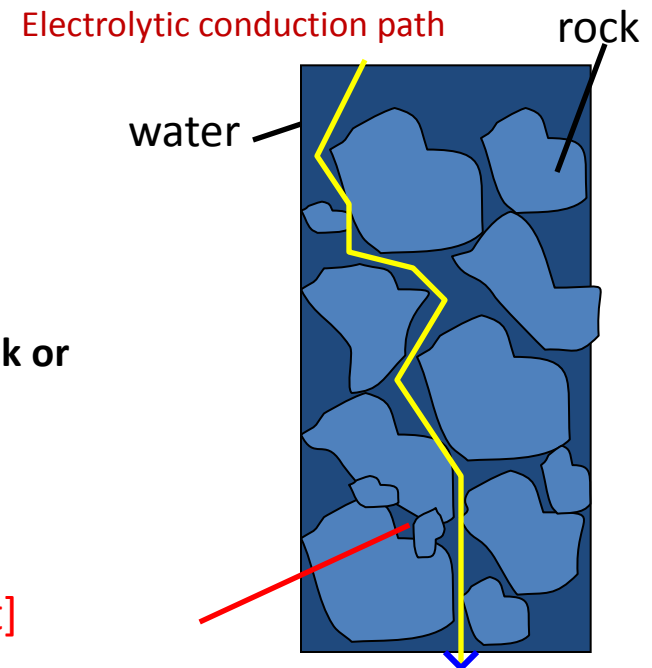
$$F = \frac{\sigma_w}{\sigma_{earth}} = \frac{\rho_{earth}}{\rho_w}$$



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

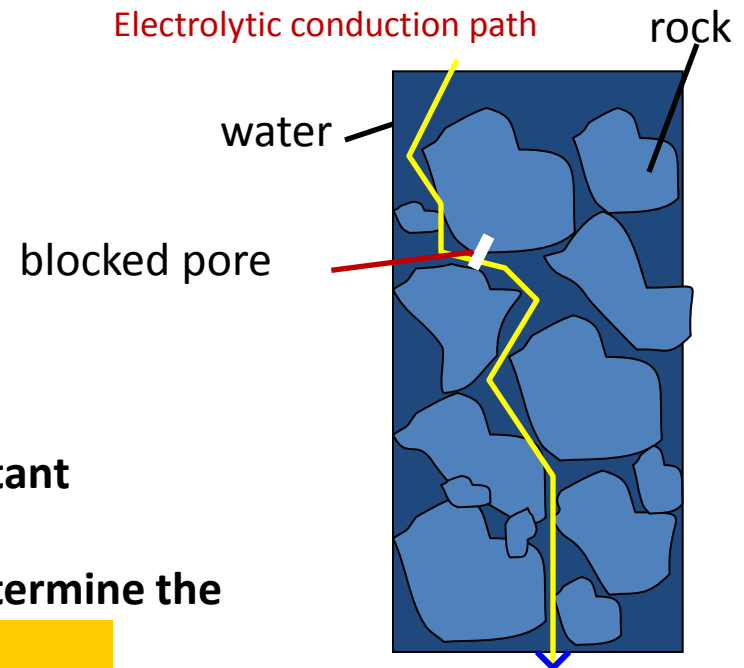
but it is only the connected pore volume that counts

[dead end pore space does not count]

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

# 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

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

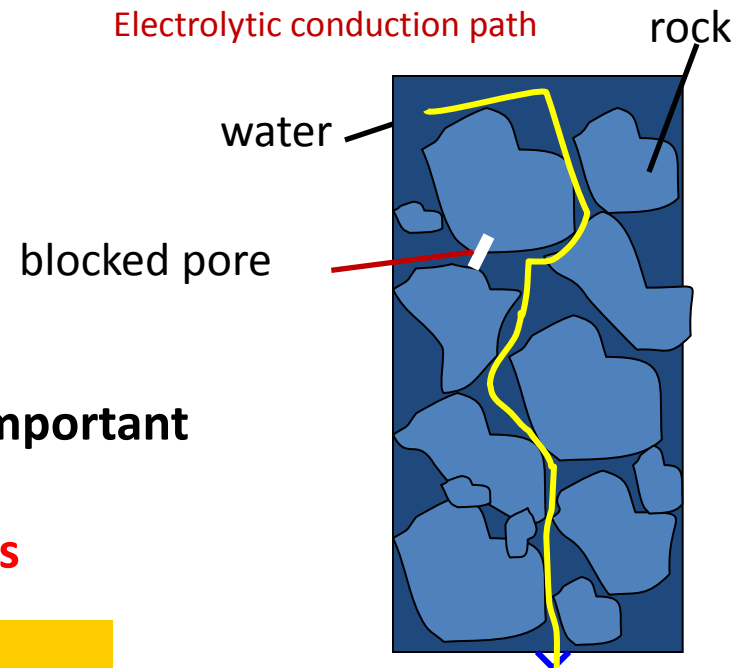
# Case 1: What does F depend upon?

- 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**

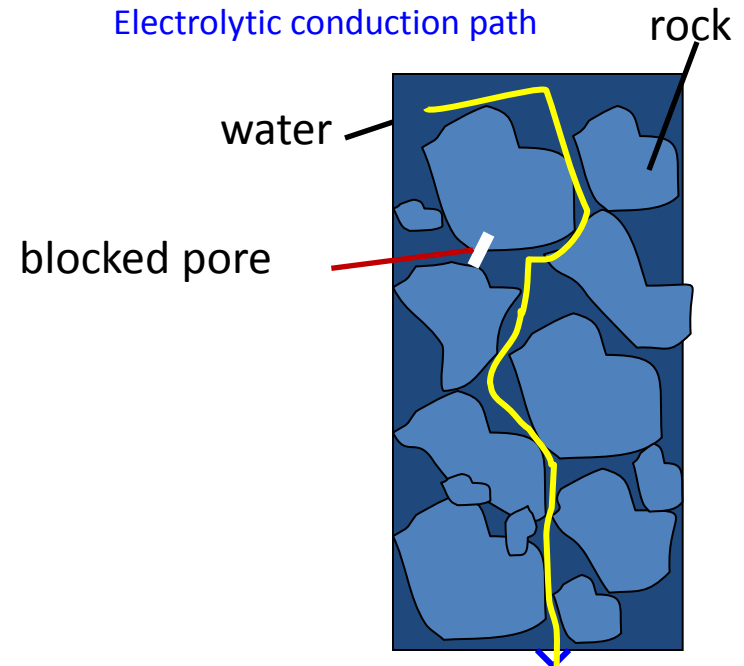
$$F = \frac{\tau}{\phi_{eff}}$$



# 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

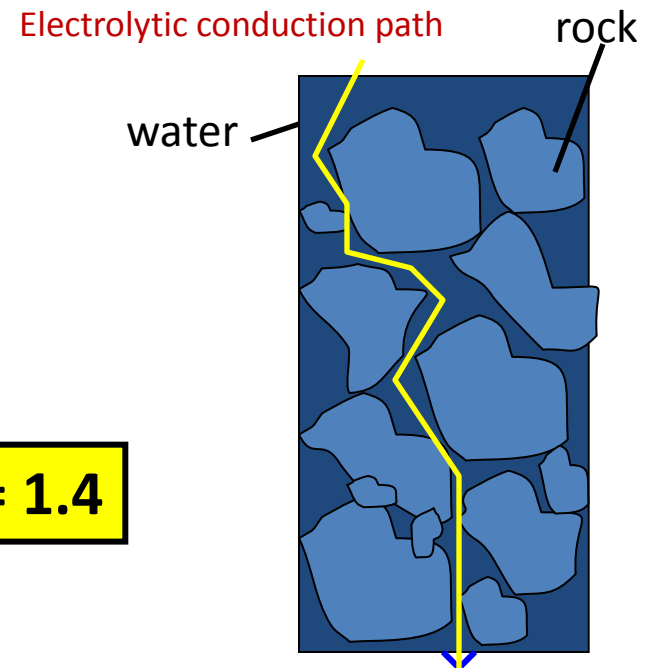
An **empirical law** based on observations - also theoretically derived (Sen, 1981)

# Case 1: Only electrolytic conduction

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

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

$$m = 1.4$$



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

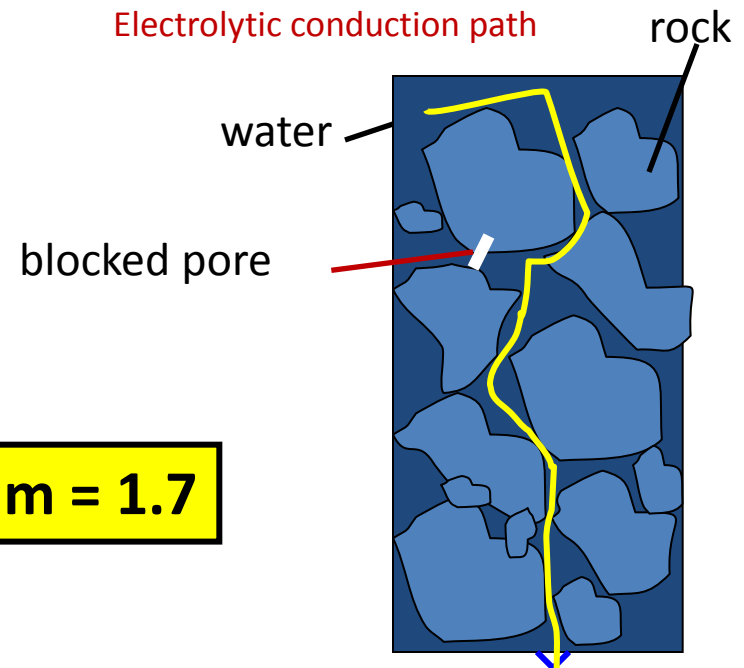
An **empirical law** based on observations - also theoretically derived (Sen, 1981)

# 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

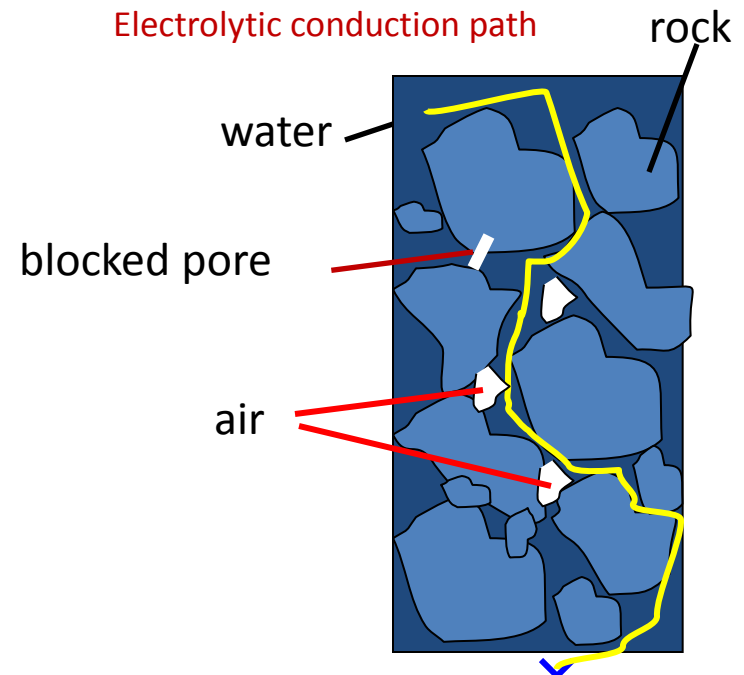
- Archie's Law (1942)  
for **unsaturated**  
**sediments**:

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

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

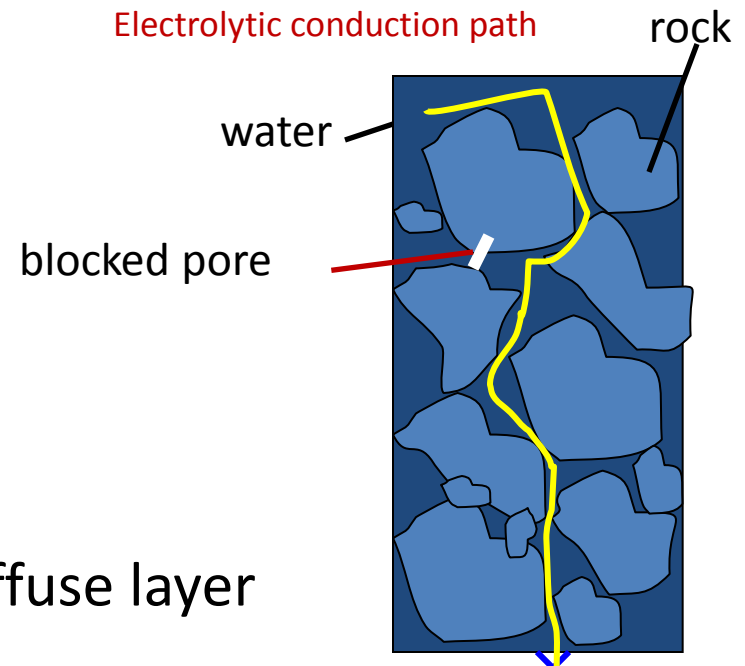
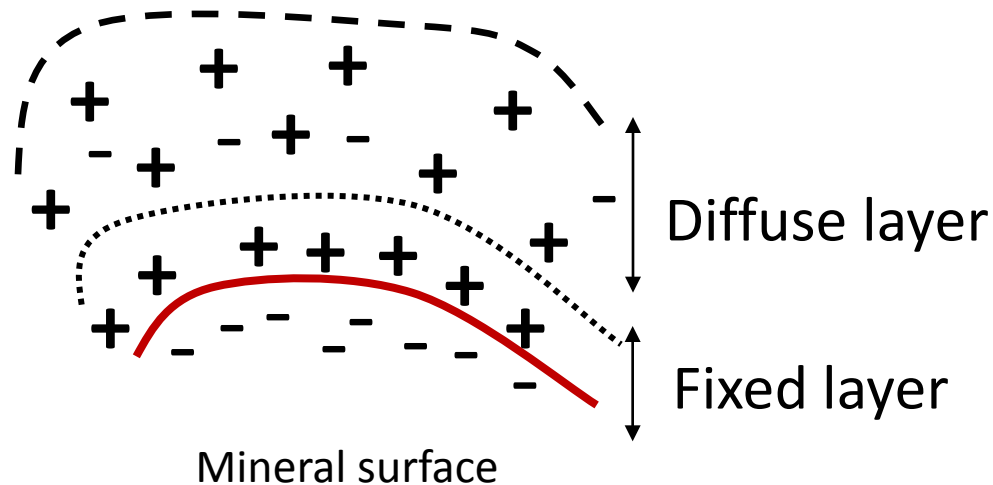
$S_w$  is the degree of saturation

$n$  is related to the rock type and distribution of air in pore space



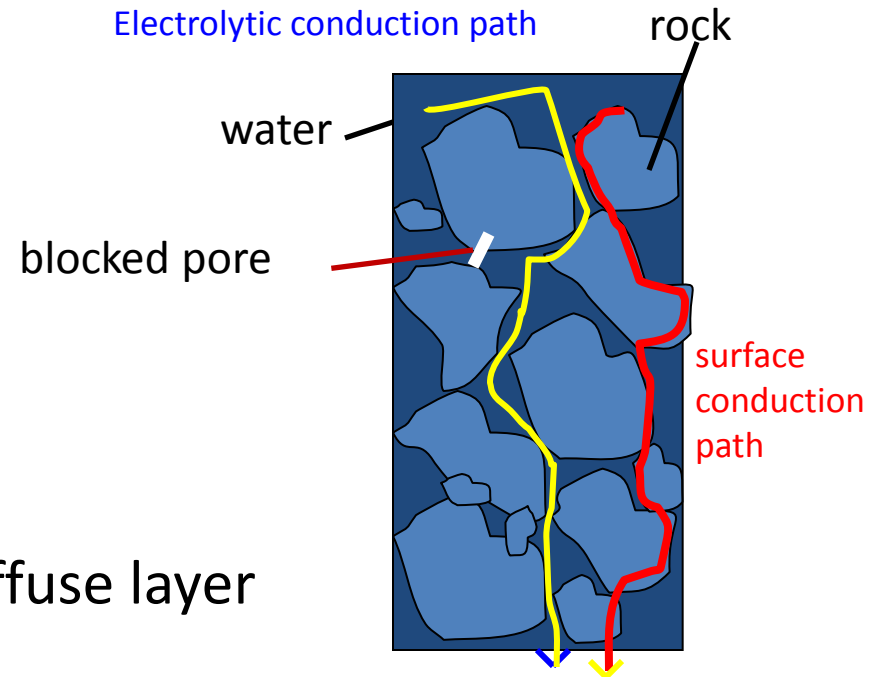
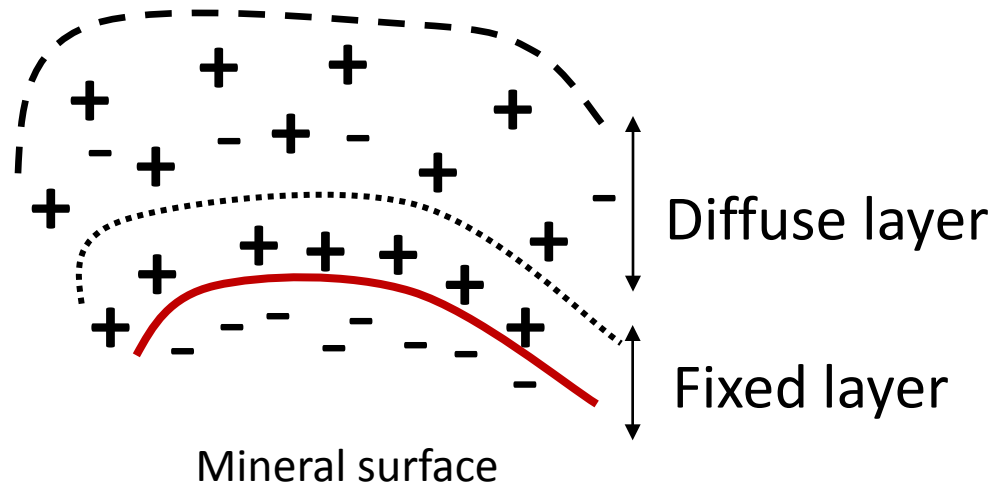
# But is the rock really non-conducting?

- 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

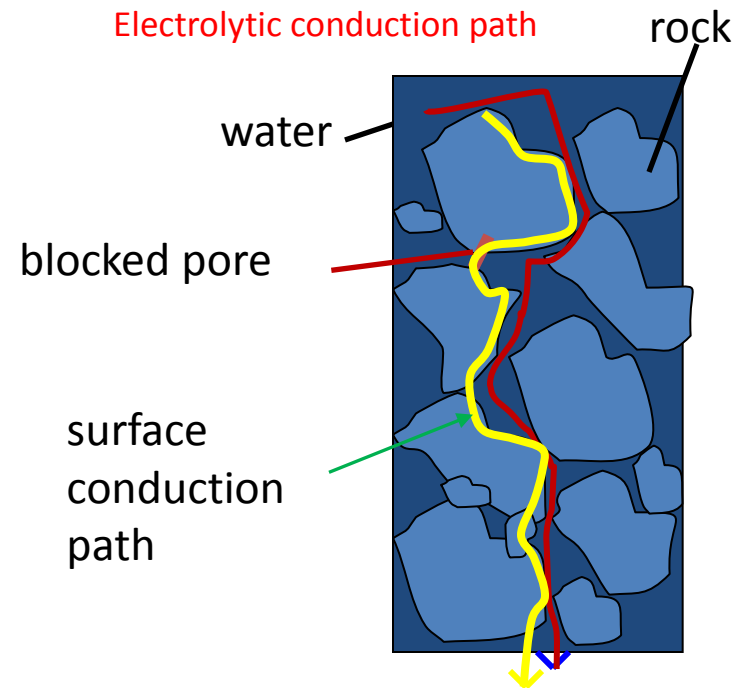
- Need modification of Archie's Law (Waxman & Smits, 1968):

Electrolytic & surface conduction paths are the same?

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

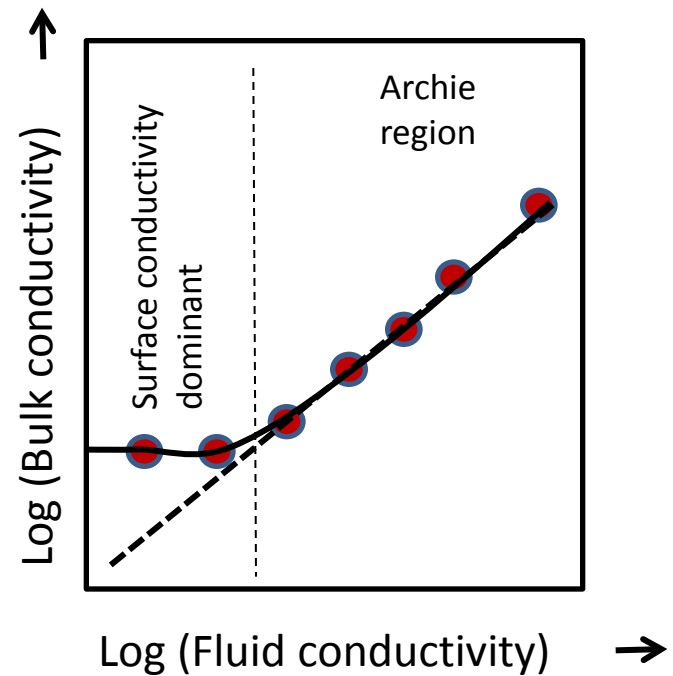
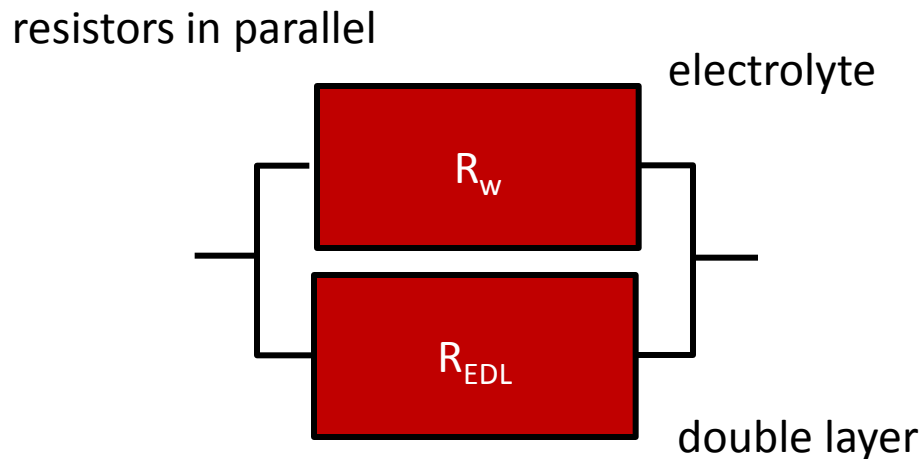
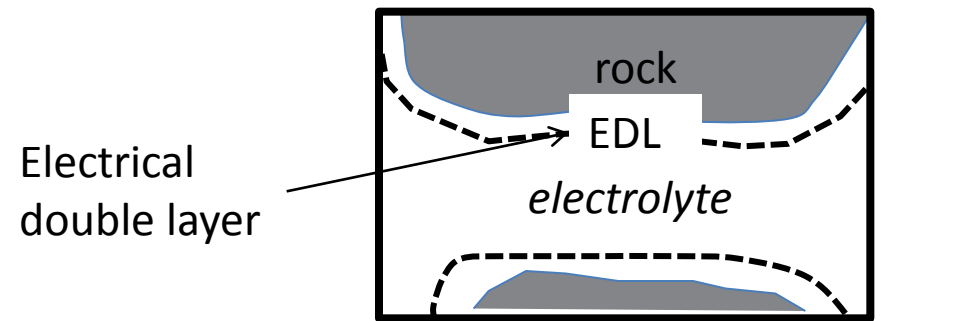
electrolytic  
conduction

surface  
conduction



[assumes that conduction pathways add in parallel]

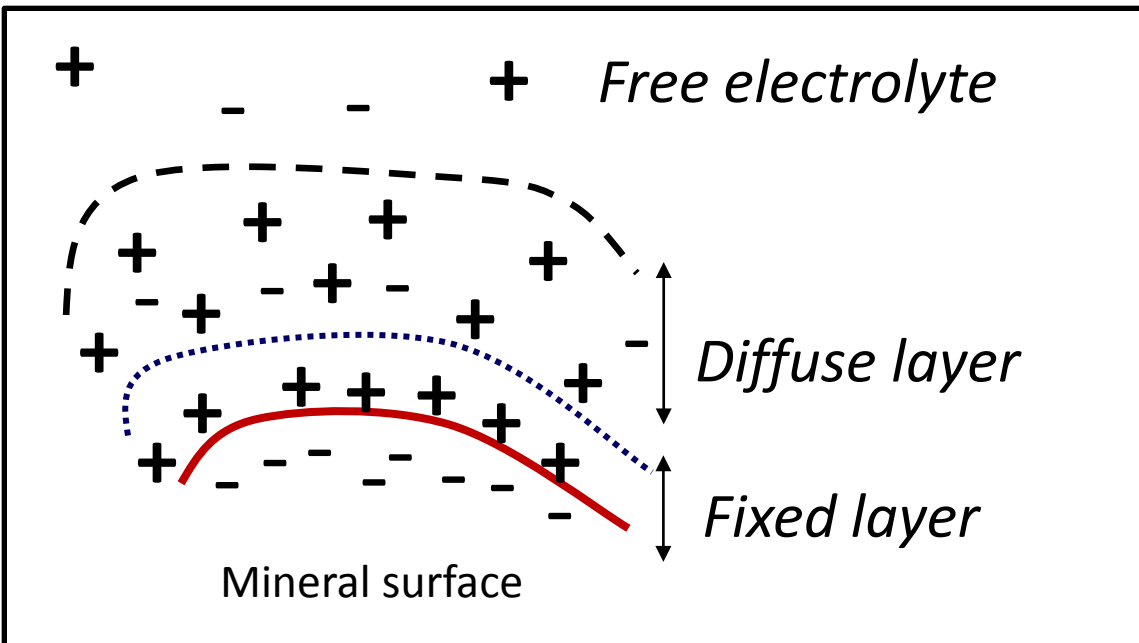
# Parallel electrolytic and surface conduction terms



# 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



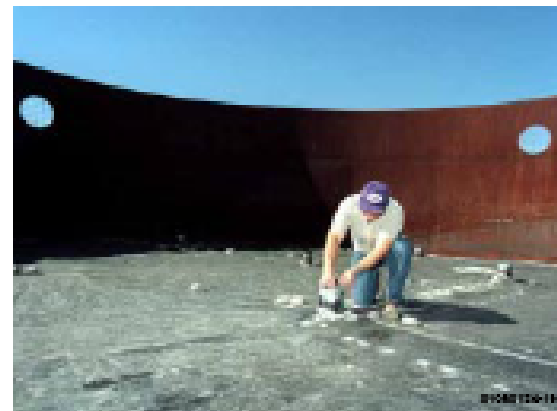
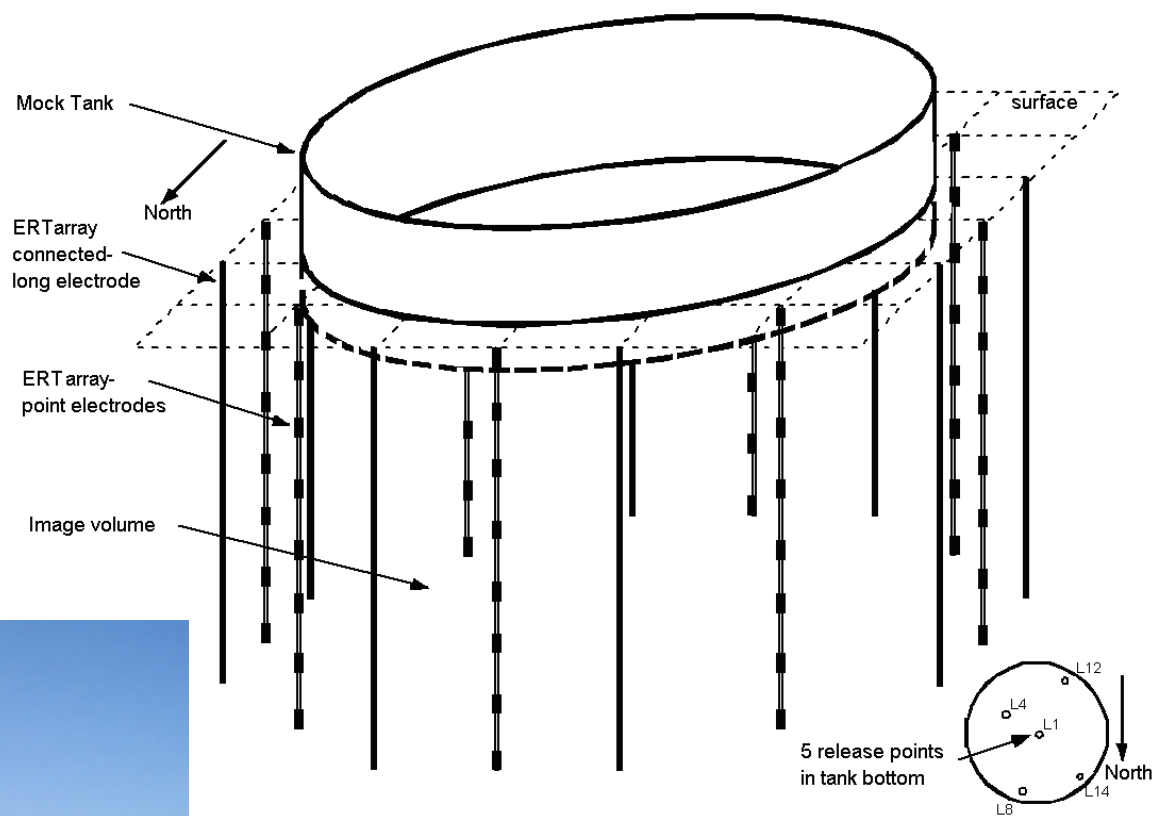
# Examples of leak detection using electrical geophysics

**Andrew Binley**  
*Lancaster University*

email: [a.binley@lancaster.ac.uk](mailto:a.binley@lancaster.ac.uk)



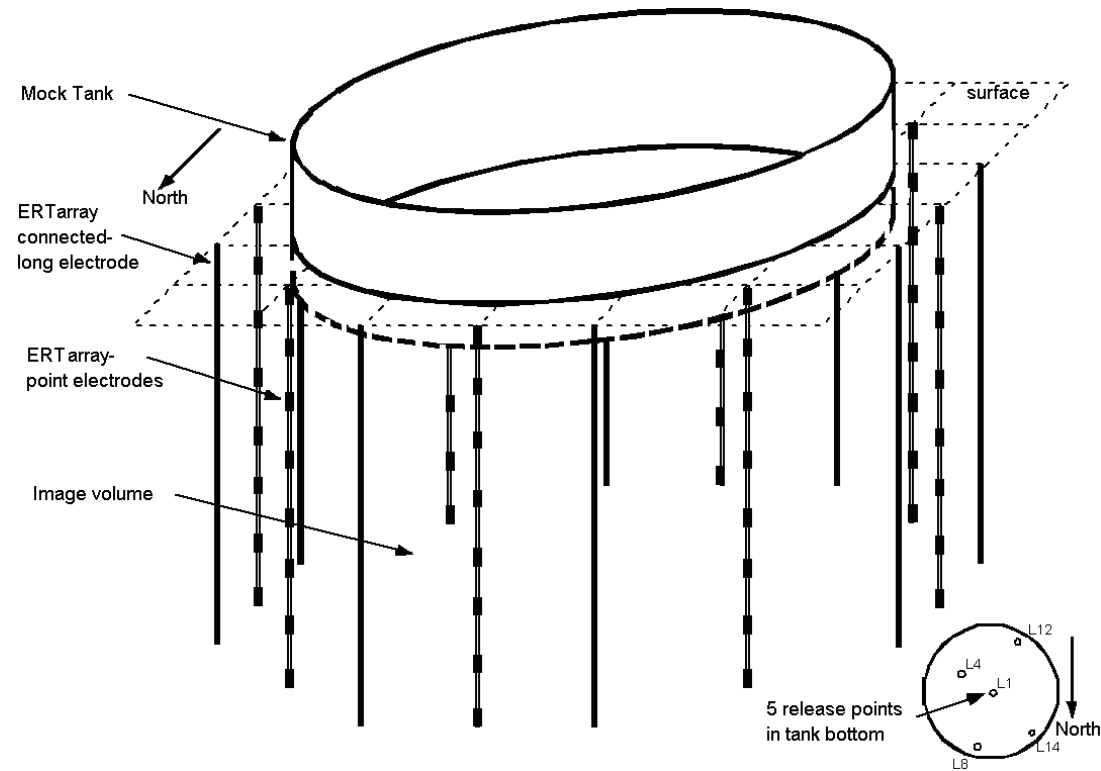
# Imaging leaks using ERT – Hanford UST





# Imaging leaks using ERT – Hanford UST

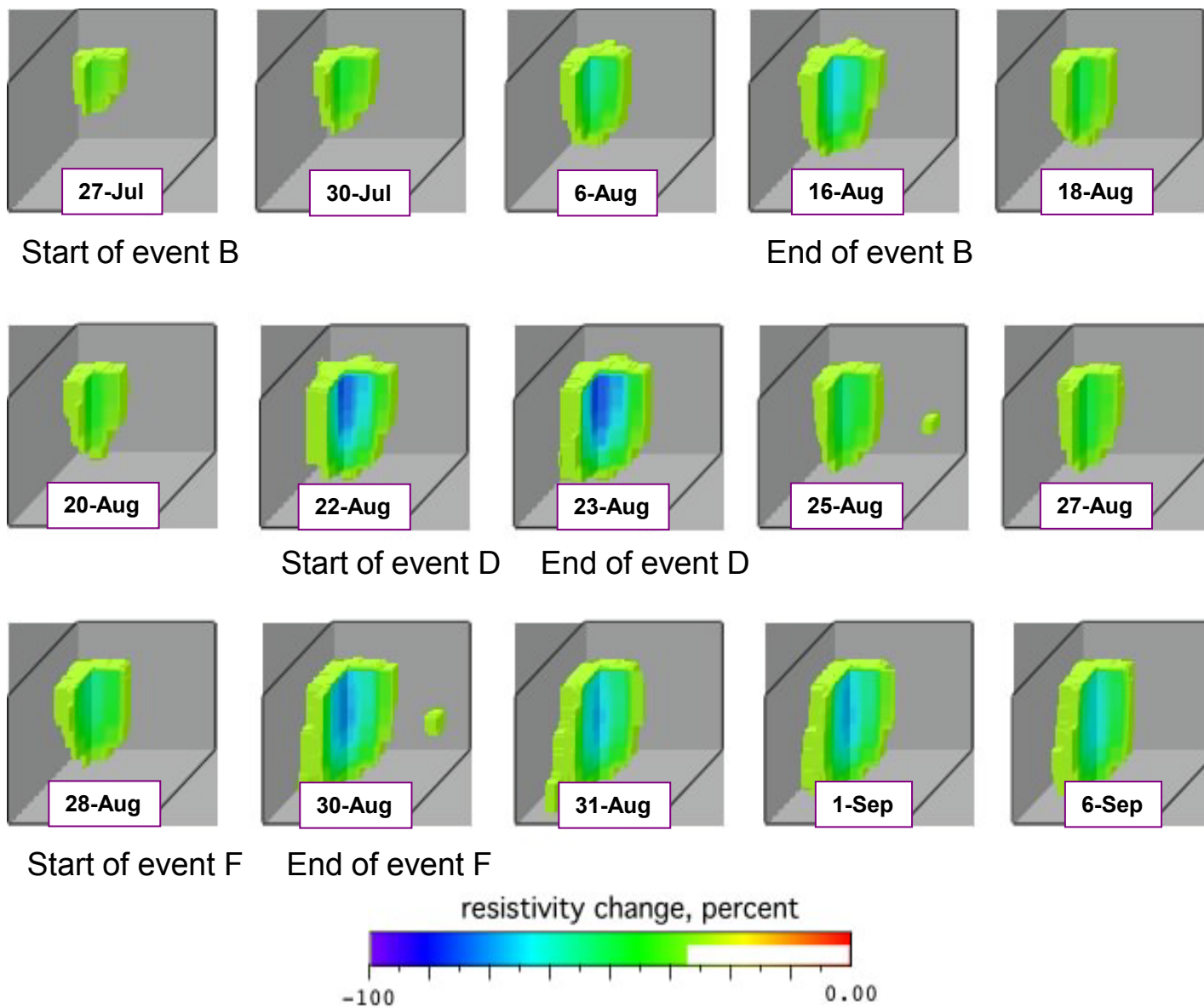
Ramirez et al.(1996) documented first trials of 3D ERT for imaging leaks from underground storage tanks at Hanford, using the 10.7m diameter “mock tank facility”.



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

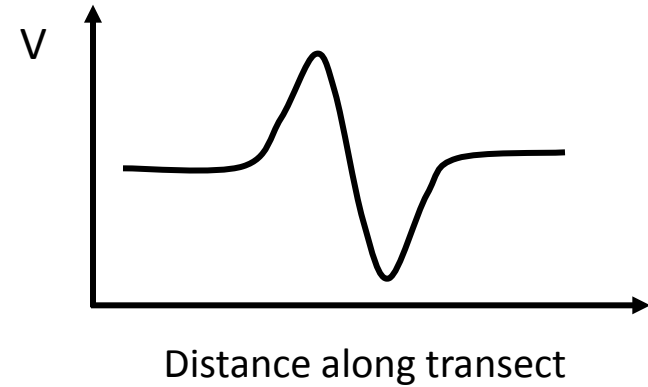
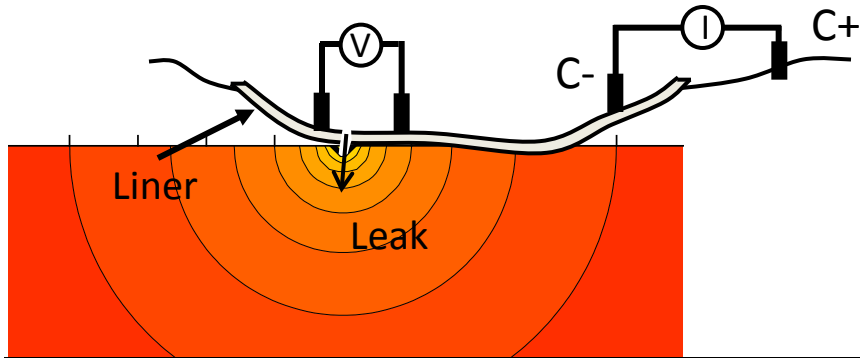
Daily et al. collected data each day (remotely), process data and inform the operators if leaks existed.

# Imaging leaks using ERT – Hanford UST



# Leak location using electrical current sources

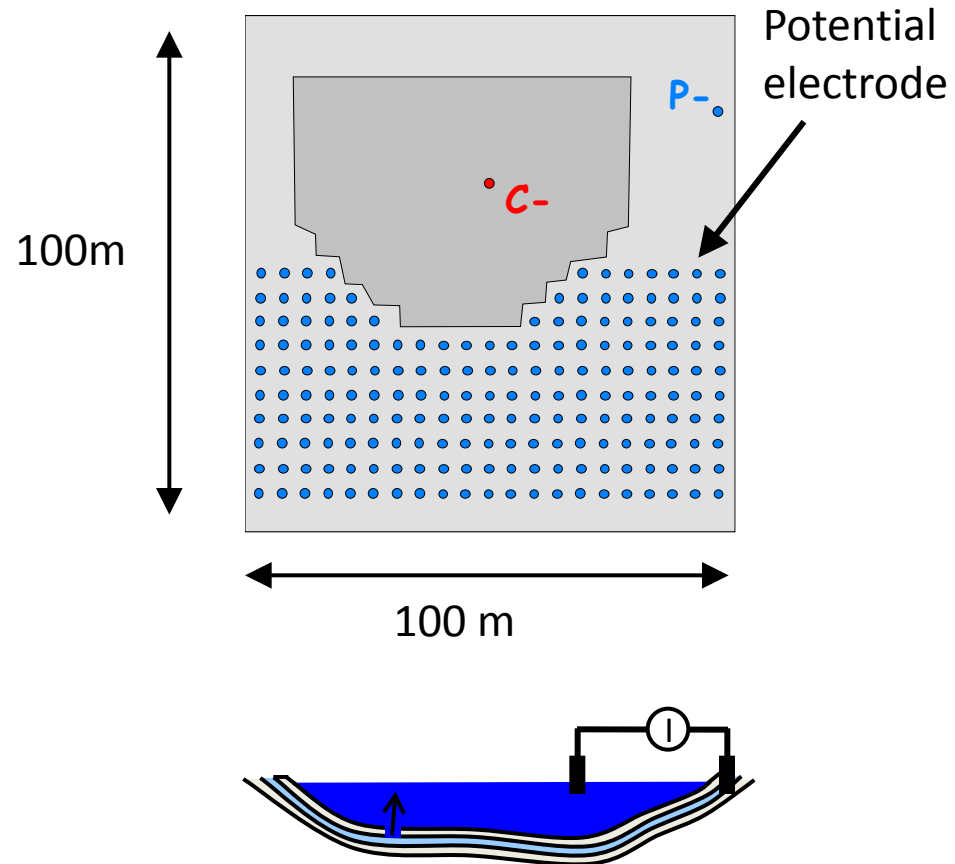
Binley et al.(1997) proposed an alternative approach in which electrical leaks were created along the hydraulic leaks and the location of these leaks then determined.



# Leak location using electrical current sources

Success of the method has been demonstrated

Mound City, MO

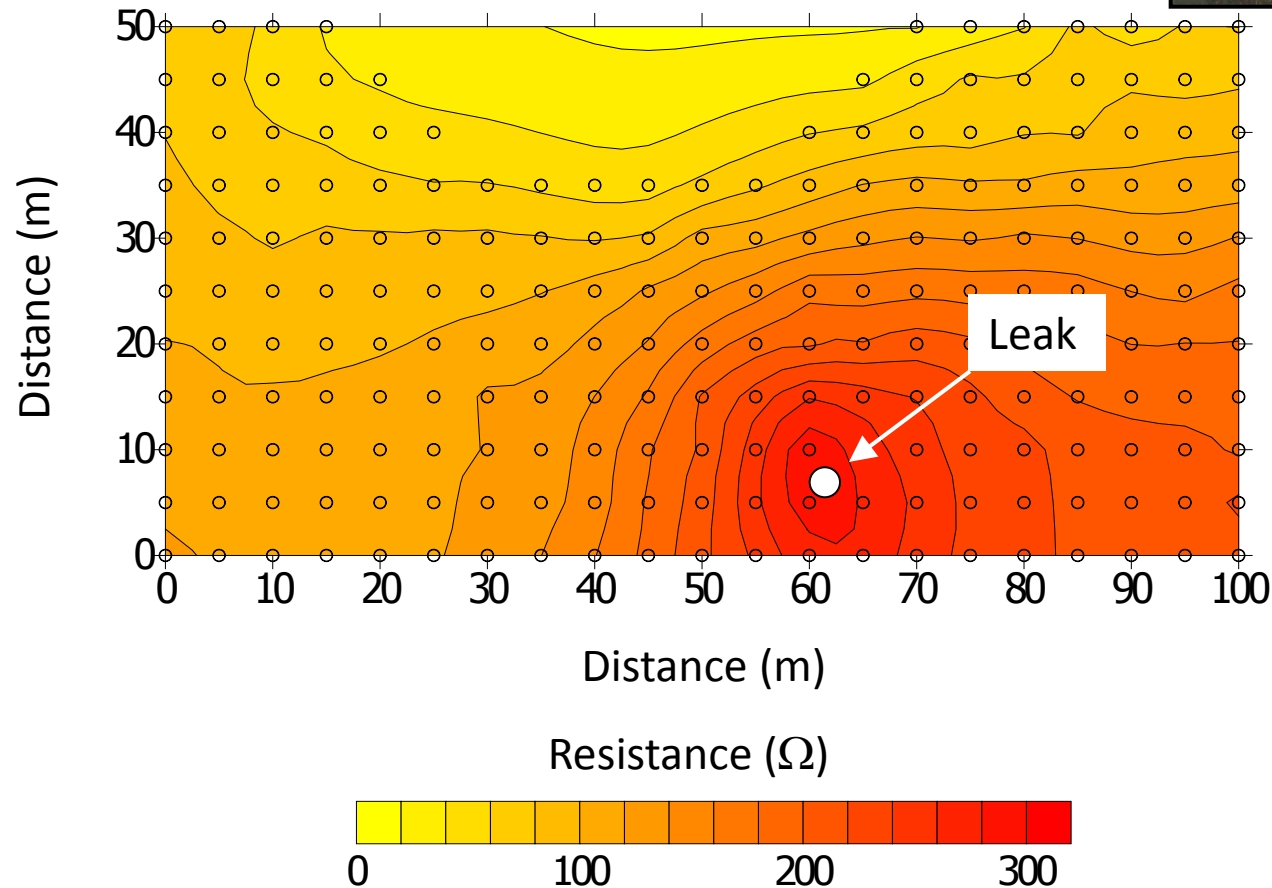


C+ electrode installed in between  
liners of double liner

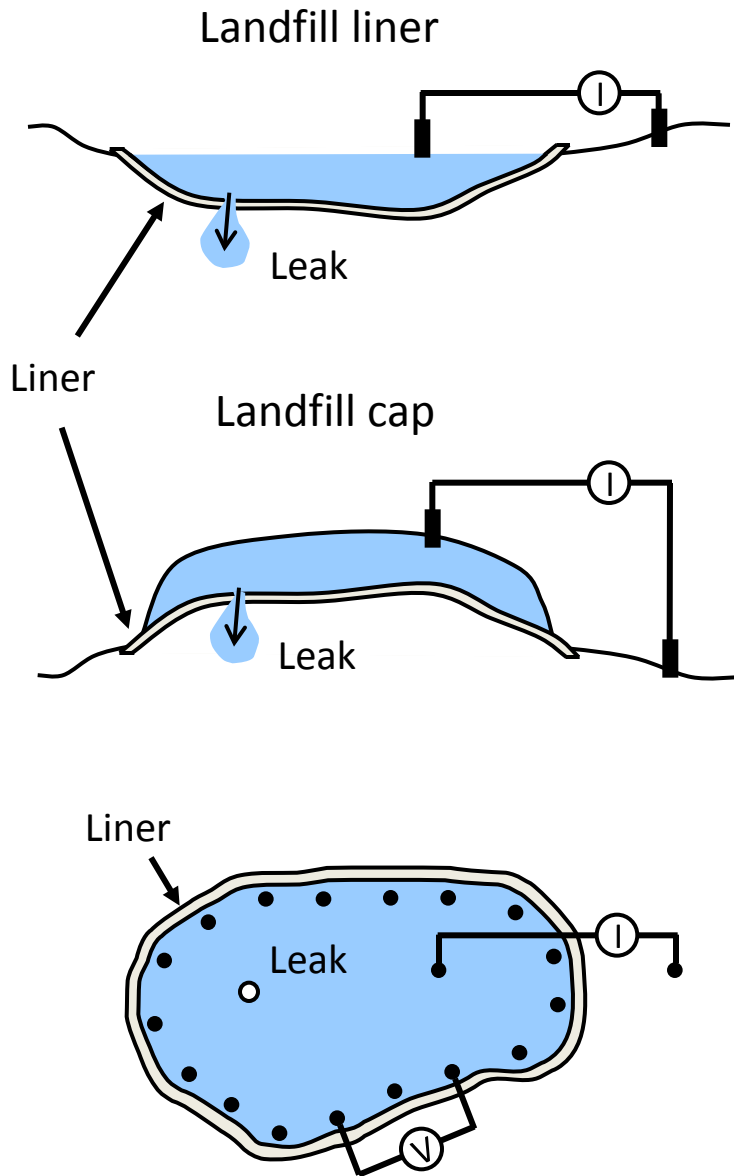


# Leak location using electrical current sources

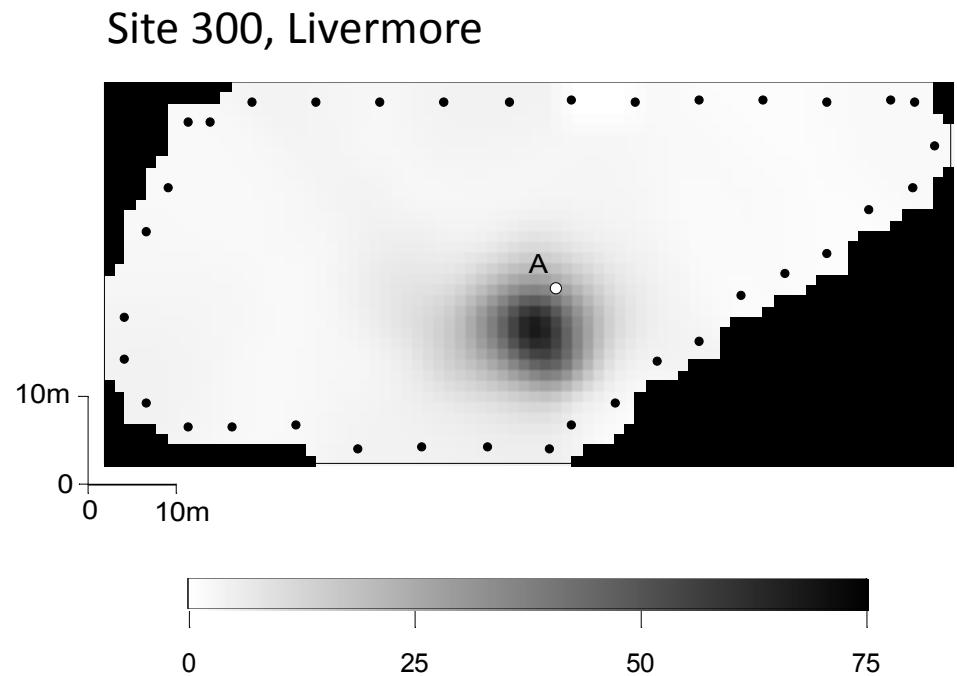
Just mapping potentials associated with current source due to a leak in a membrane



# Leak location using electrical current sources



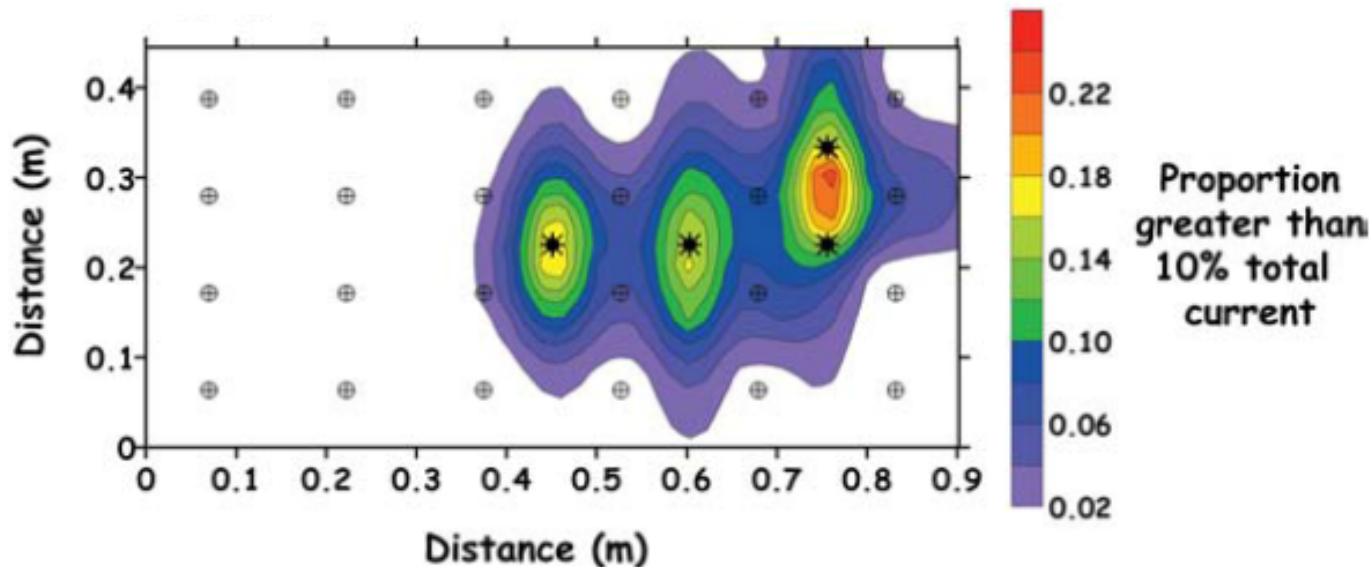
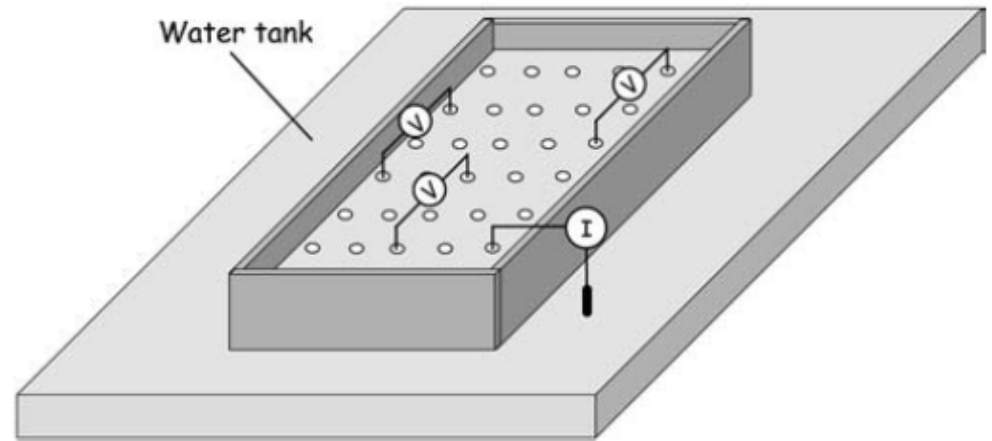
In cases where access inside or underneath the storage facility is not possible then we can use perimeter electrodes and determine, using inverse methods, the location of the current sources (leaks)



*Binley, Daily and Ramirez (1997)*

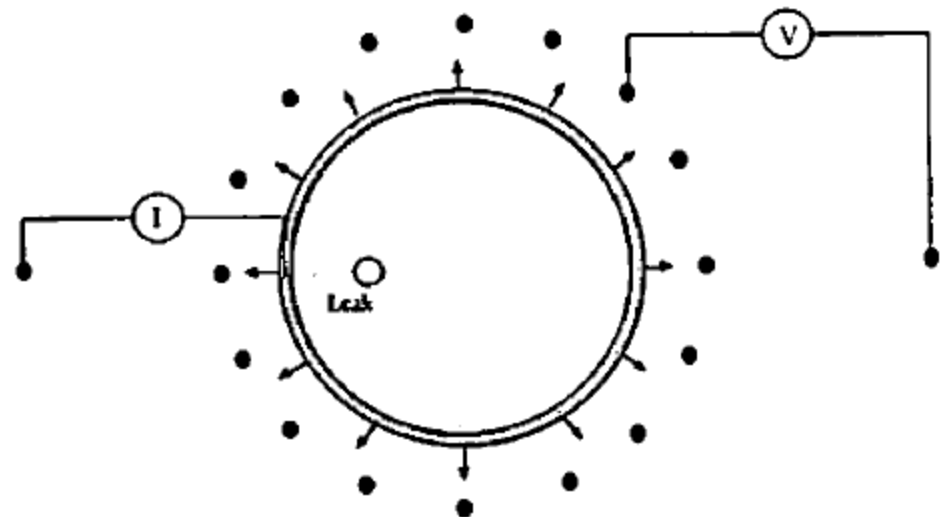
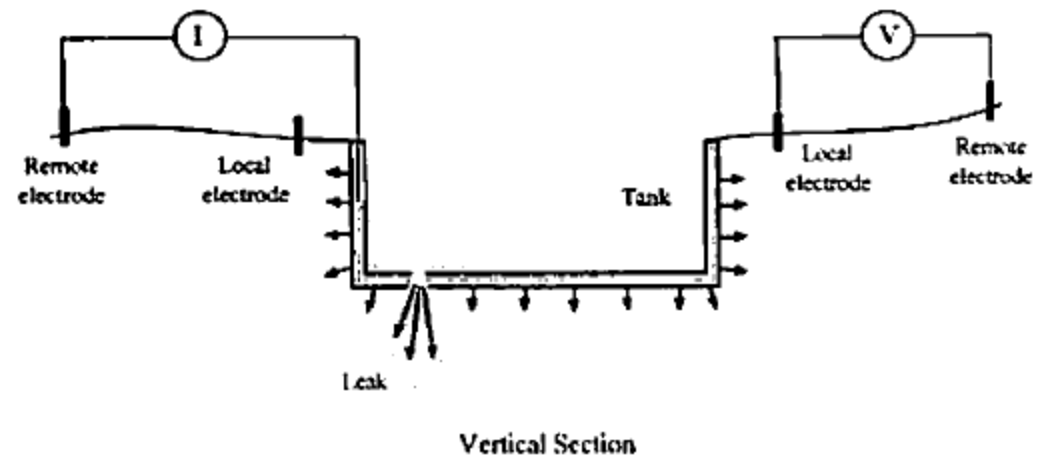
# Leak location using electrical current sources

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.



# Leak location using electrical current sources

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





## 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.

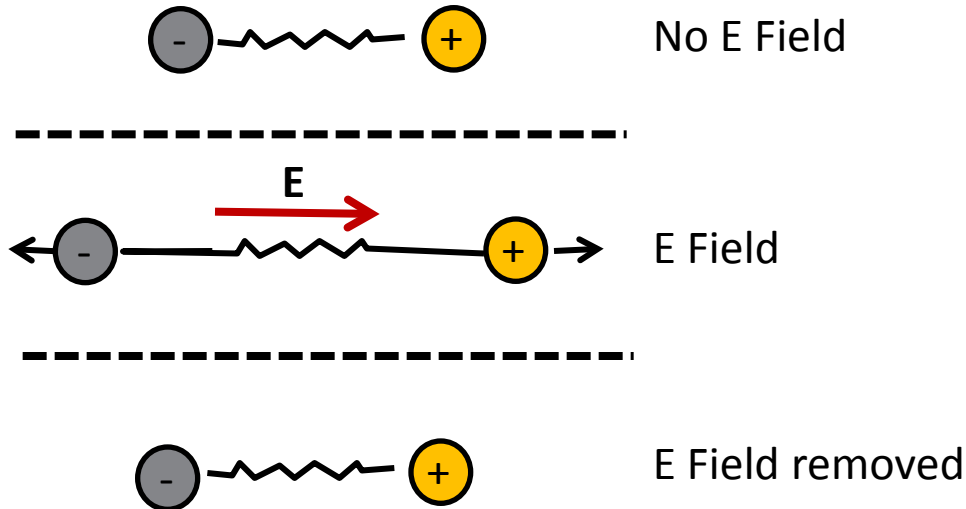
**EXTRA MATERIAL**

Interpretation of ground penetrating radar (GPR) measurements

## **2.2. HIGH FREQUENCY ELECTRICAL PROPERTIES**

# Displacement Currents

- Storage of Energy



$$J = \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

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,  $\epsilon$
- Conductivity,  $\sigma$
- Permeability,  $\mu$

$$\epsilon_r = \epsilon/\epsilon_0 \text{ (1-80)}$$

$$\mu_r = \mu/\mu_0 \approx 1$$

$$\sigma \approx 0.0001\text{-}10 \text{ S/m}$$

$$\epsilon_0 = \text{permittivity of free space } (8.854 \times 10^{-12} \text{ F/m})$$

$$\mu_0 = 4\pi \cdot 10^{-7} \text{ H/m}$$

# Controlling factors on velocity of radar wave:

The full expression:

$P$  = loss factor

$c = 0.3$  m/ns

$\epsilon_r$  = **relative dielectric constant**

$\mu_r$  = relative magnetic  
permeability

$\epsilon_o$  = permittivity of free space  
( $8.854 \times 10^{-12}$  F/m)

$\sigma$  = conductivity

$f$  = frequency in Hz

$$V = \frac{c}{\left\{ \frac{\epsilon_r \mu_r}{2} \left[ (1 + P^2) + 1 \right] \right\}^{1/2}}$$
$$P = \frac{\sigma}{\omega \epsilon}$$
$$\epsilon = \epsilon_r \epsilon_o$$
$$\omega = 2\pi f$$

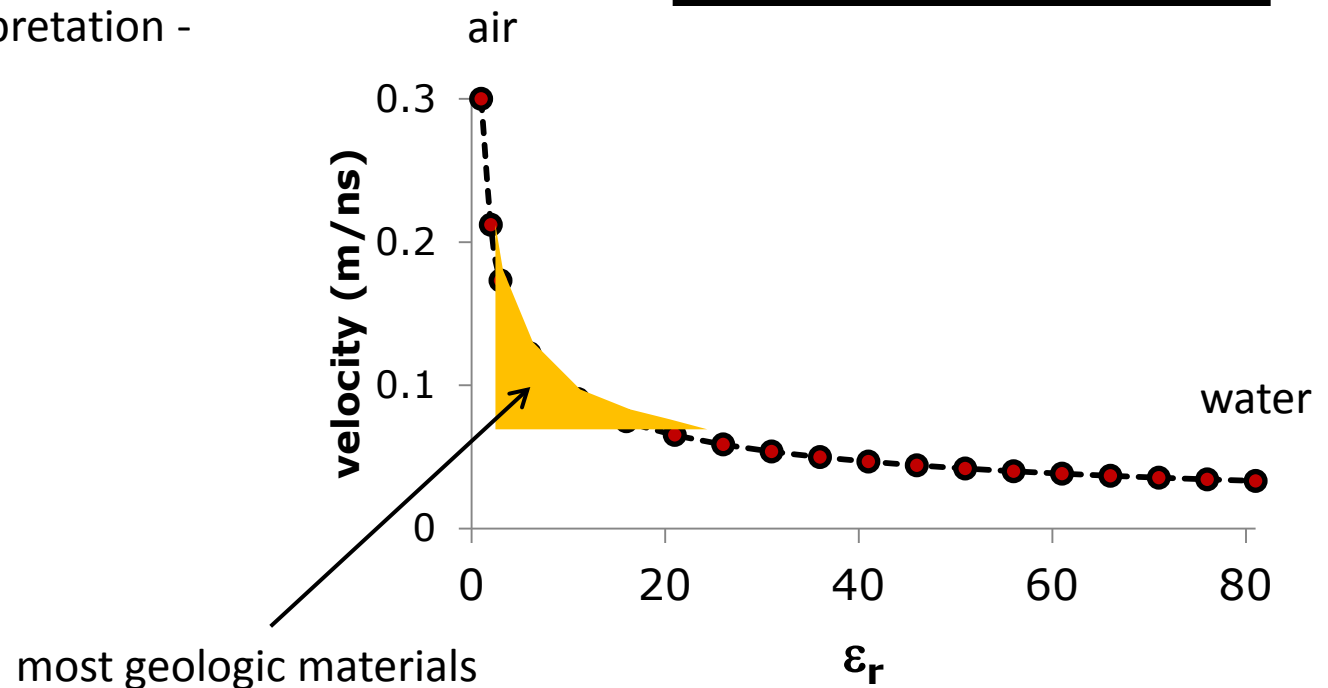
In low loss materials ( $P \cong 0$ ) often assumed:

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

## Relationship between permittivity and velocity

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

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



# Relative dielectric constant for various geologic materials

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

Material	$\epsilon_r$	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  $\theta$  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 ( $\sim 5$ -50%)

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

assuming low-loss material and  $\varepsilon_s \approx 3$ -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)
- $$\varepsilon' = a + b\theta_v + c(\theta_v^2) - d(\theta_v^3)$$
- 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

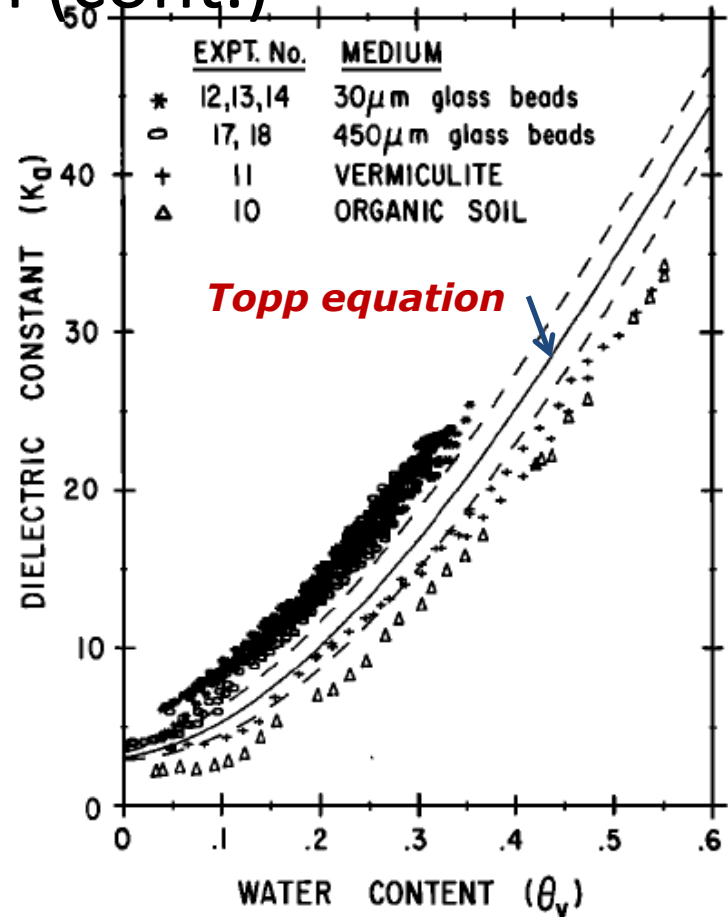
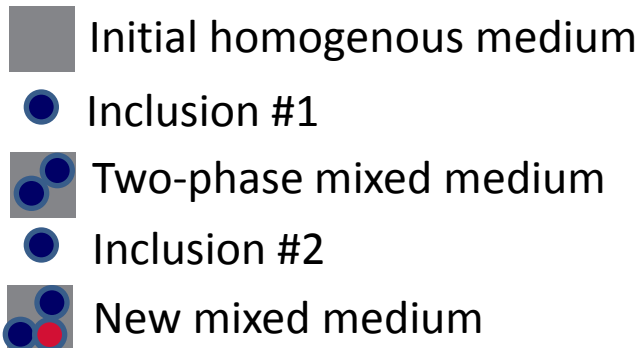
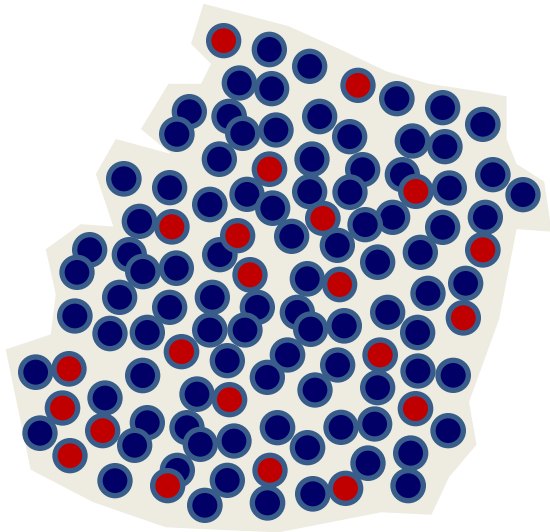


Fig. 6. The measured relationship between  $K_a$  and  $\theta_v$  for the mineral soils, 30  $\mu\text{m}$  glass beads, ground vermiculite, and an organic soil. The area between the dashed lines is the same region as between the dashed lines in Figure 4.

# Mixing models



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

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## 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

$\phi$  = porosity  
 $\theta$  = moisture  
content

EM wave parallel to bedding  $\alpha = 1$   
EM wave perpendicular to bedding  $\alpha = 0.5$

*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