International Research School of Water Resources

International PhD Course in

HYDROGEOPHYSICS

Resistivity & IP methods

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Overview

We have demonstrated links between hydrological and geophysical properties and show the potential value of measuring resistivity and induced polarisation (IP) as a means of determining information about hydrological structures and/or states.

Here we present approaches for measurement of resistivity and IP.

We cover:

- the basic background to the measurement principle;
- measurement approaches and limitations;
- example applications.

Resistivity basic measurement principles

Measurements are *usually* done at low frequency (DC resistivity).

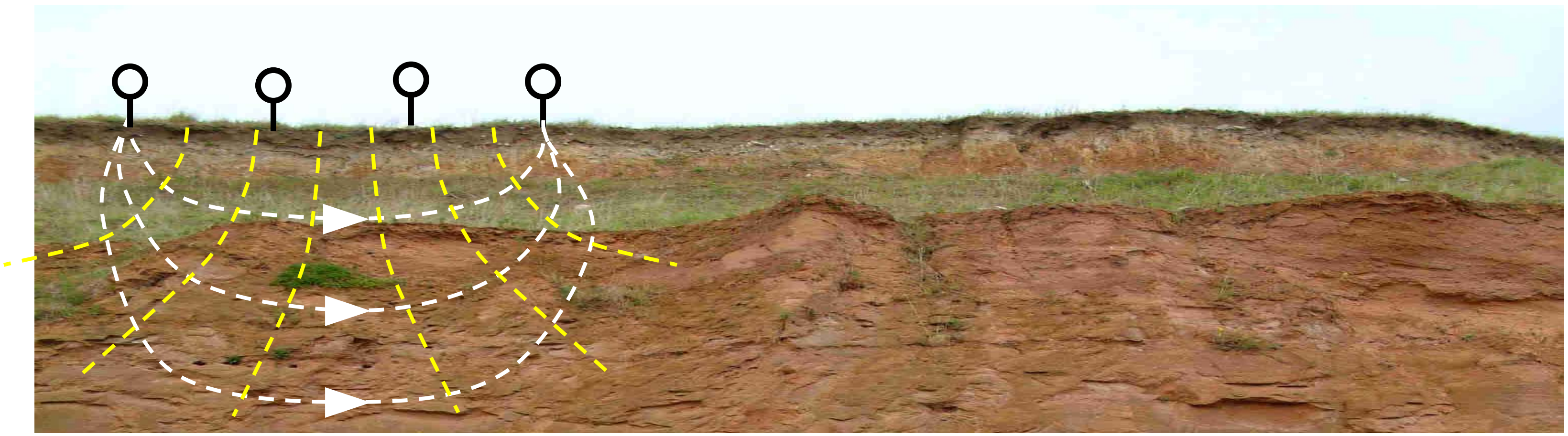
Four electrodes are used:

C+ source current, C- sink current

P+ potential measurement (positive)

P- potential measurement (negative)

C+ P+ P- C-



Current is injected between C+ and C-
The voltage difference between P+ and P- is measured

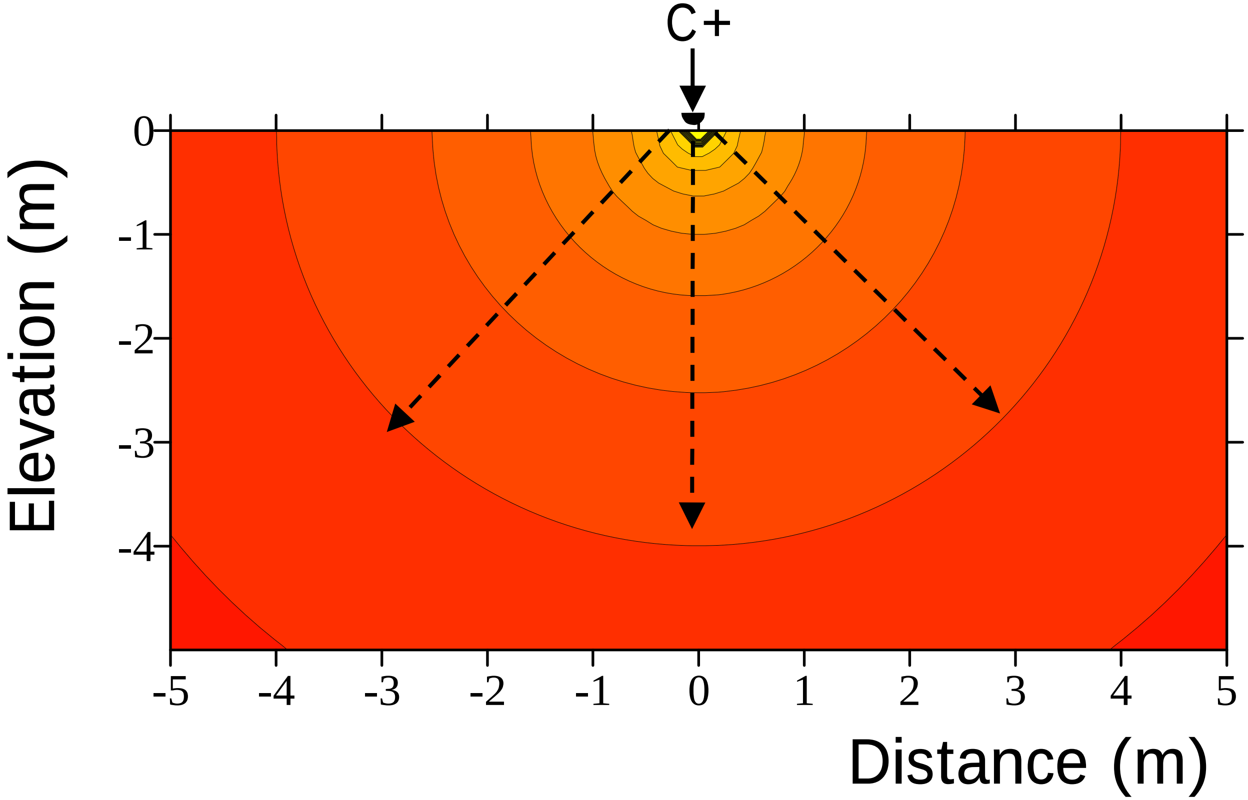
The voltage difference is a function of the current injected and the resistivity beneath the electrode array

The voltage V due to current injection I in the subsurface with electrical conductivity $\sigma\,(=1/\rho)$ satisfies:

$$\nabla \cdot (\sigma \nabla V) = -I\,\delta(\mathbf{r})$$

If σ is uniform then current injection at the surface leads to:

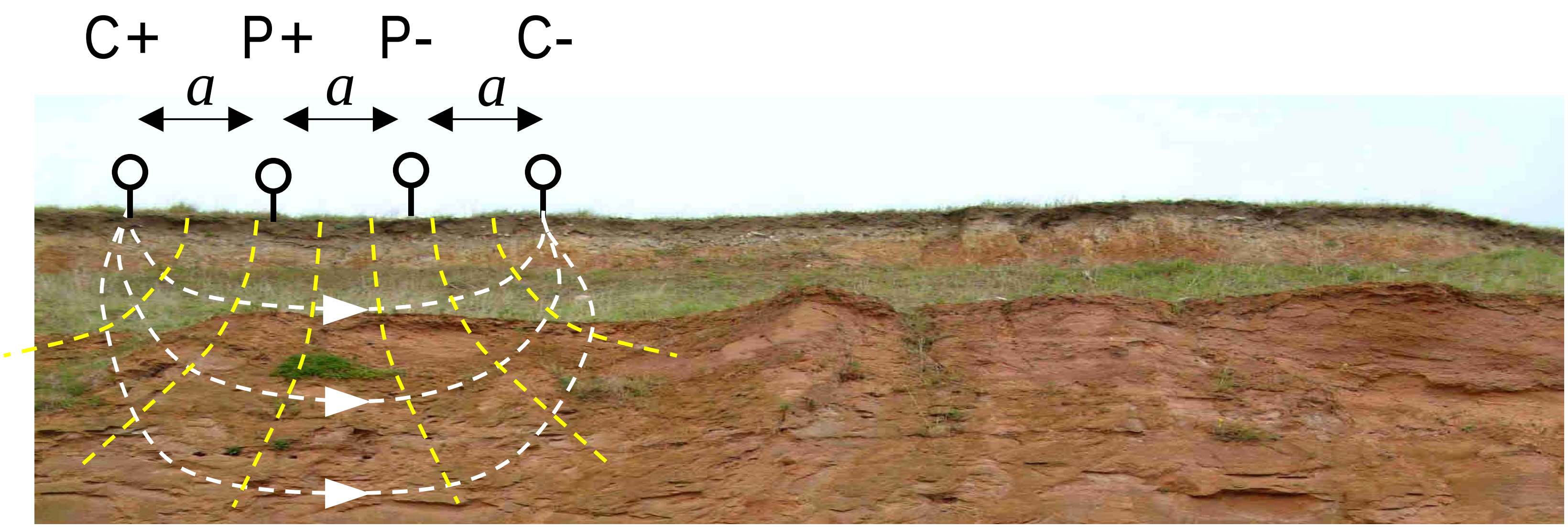
$$V = \frac{\rho I}{2\pi} \cdot \frac{1}{r}$$



For a pair of current electrodes (dipole) we can then determine the *apparent* resistivity given the measured potential difference (dipole) for a given injected current.

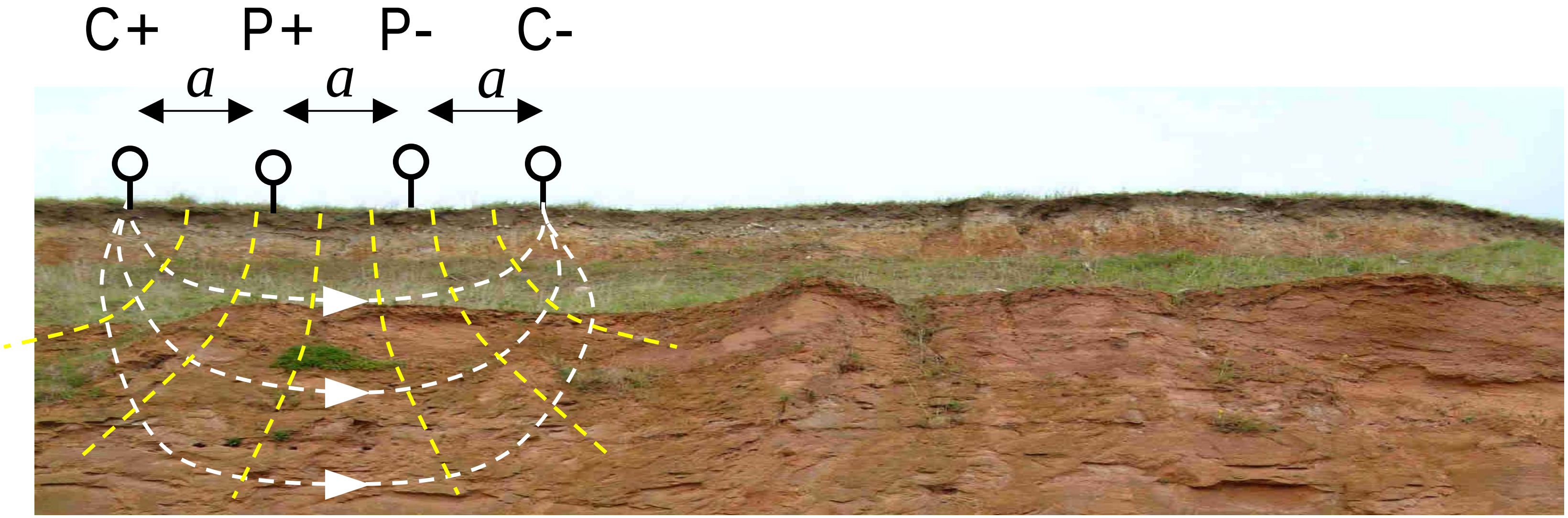
For the arrangement below: $\rho_a = 2\pi a R$

Where R is the transfer resistance $\dfrac{V(\mathrm{P+}) - V(\mathrm{P-})}{I}$



The *apparent* resistivity is the equivalent resistivity if the ground is uniform and is a useful way of expressing measured data (and also for plotting surface data as we will see later)

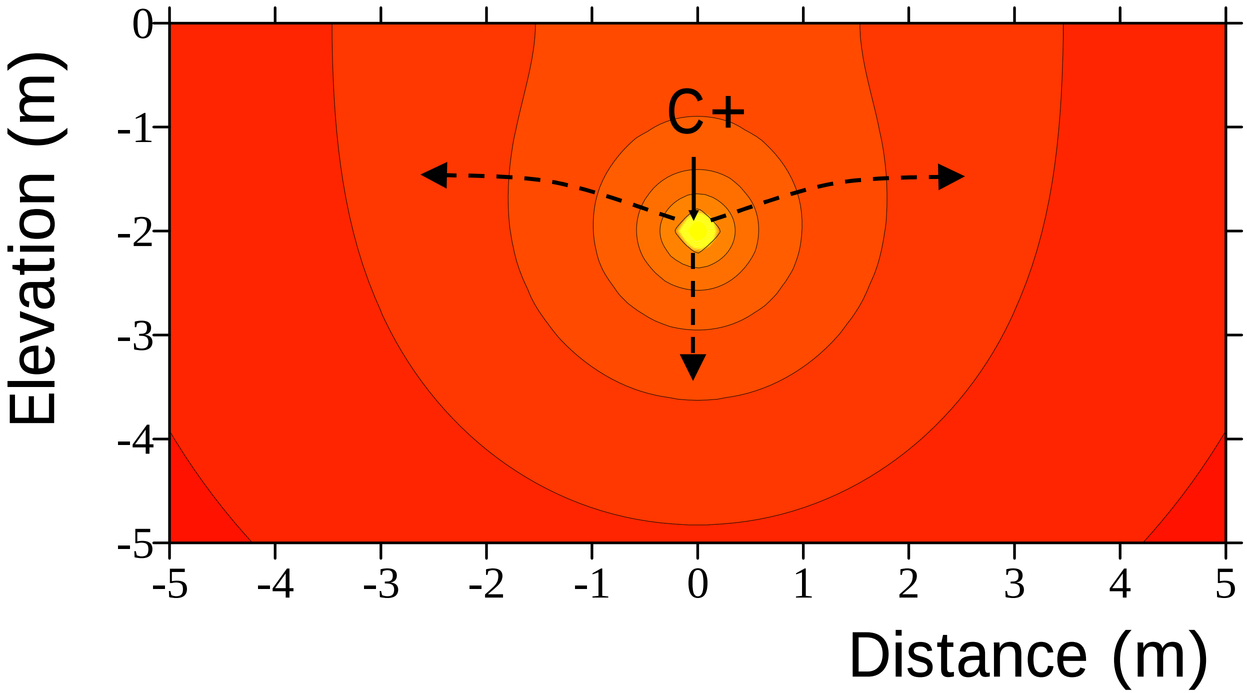
$$\rho_a = 2\pi a R$$



We can also compute the analytical solution to

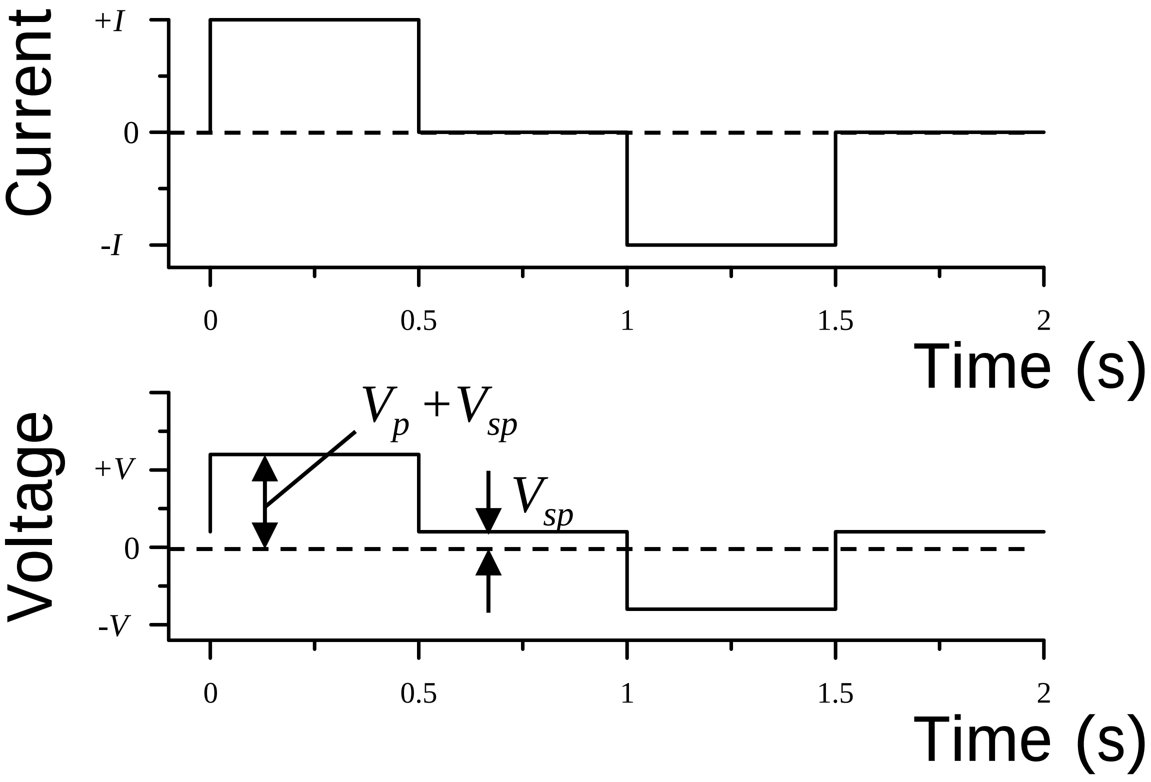
$$\nabla \cdot (\sigma \nabla V) = -I\,\delta(\mathbf{r})$$

Even if the electrode is not on the surface. To do this we make use of an imaginary source above the ground and use superposition (just as in pumping test analysis)

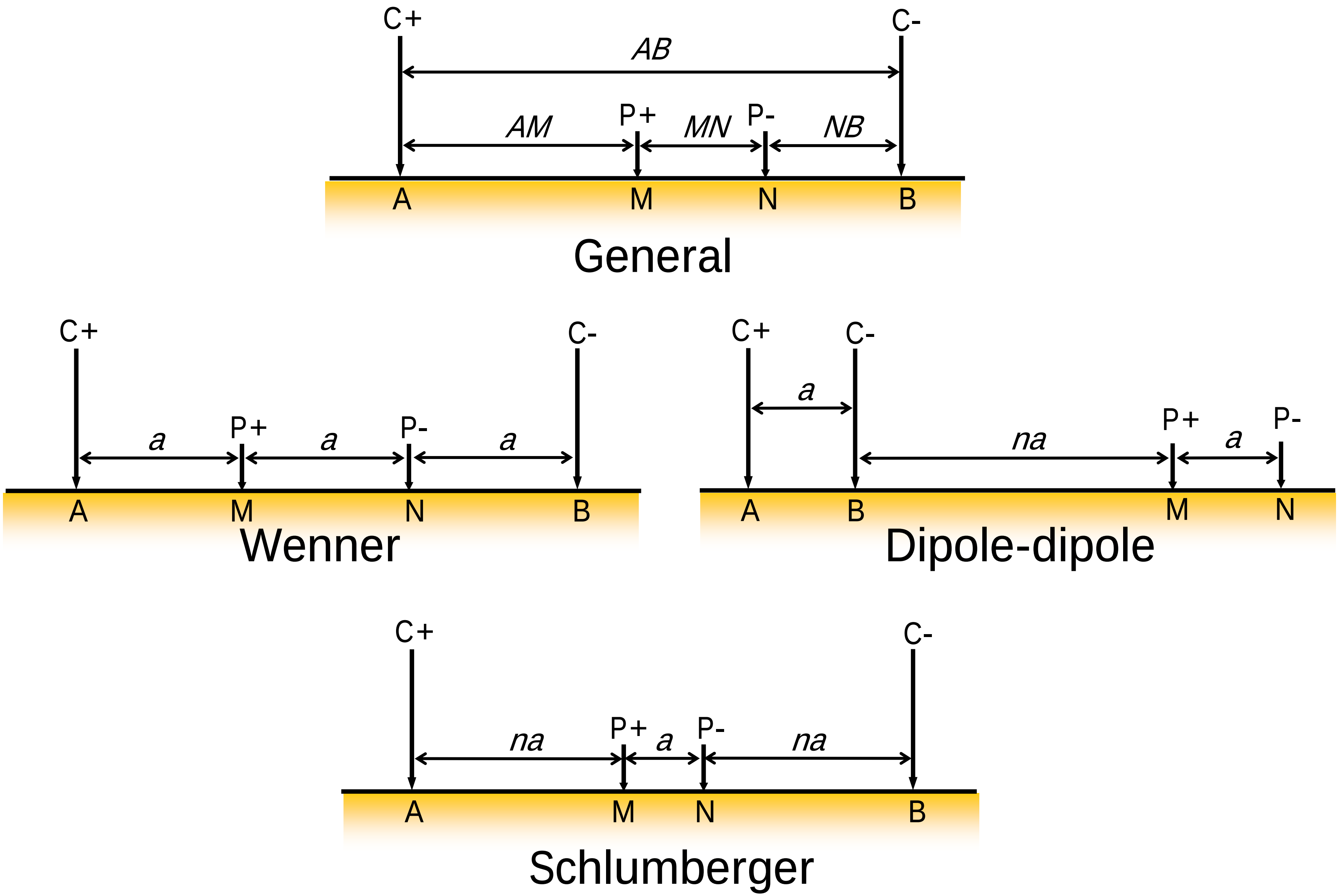


Current is normally injected as a switched square wave

Why is this ?

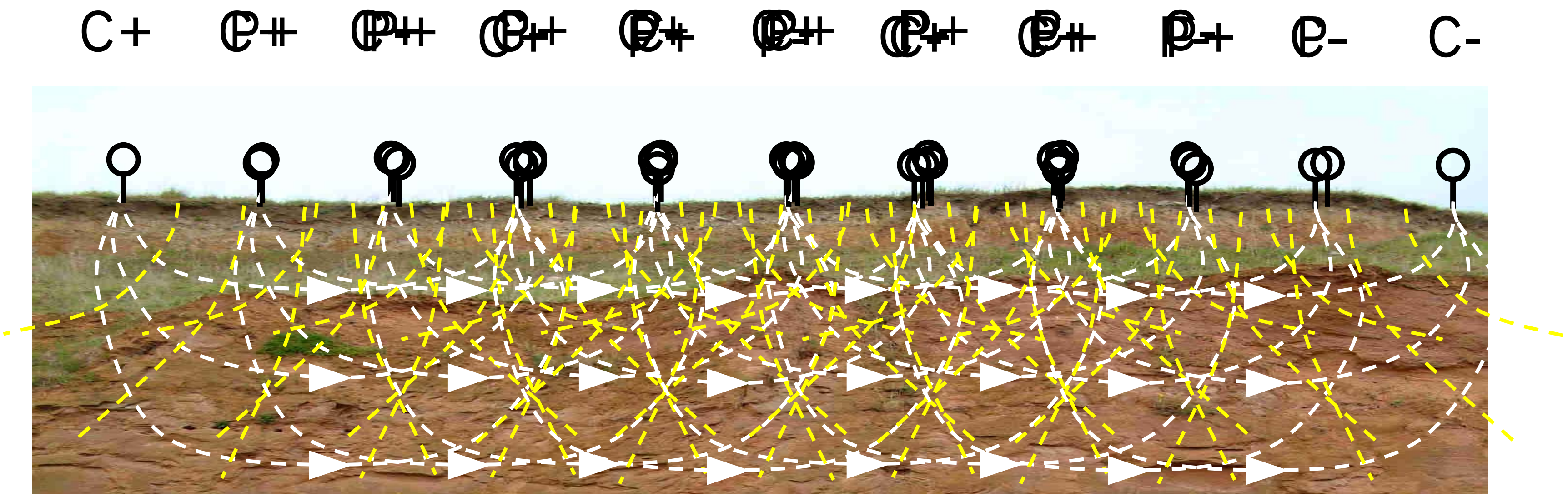


Various surface measurement configurations



Resistivity profiling

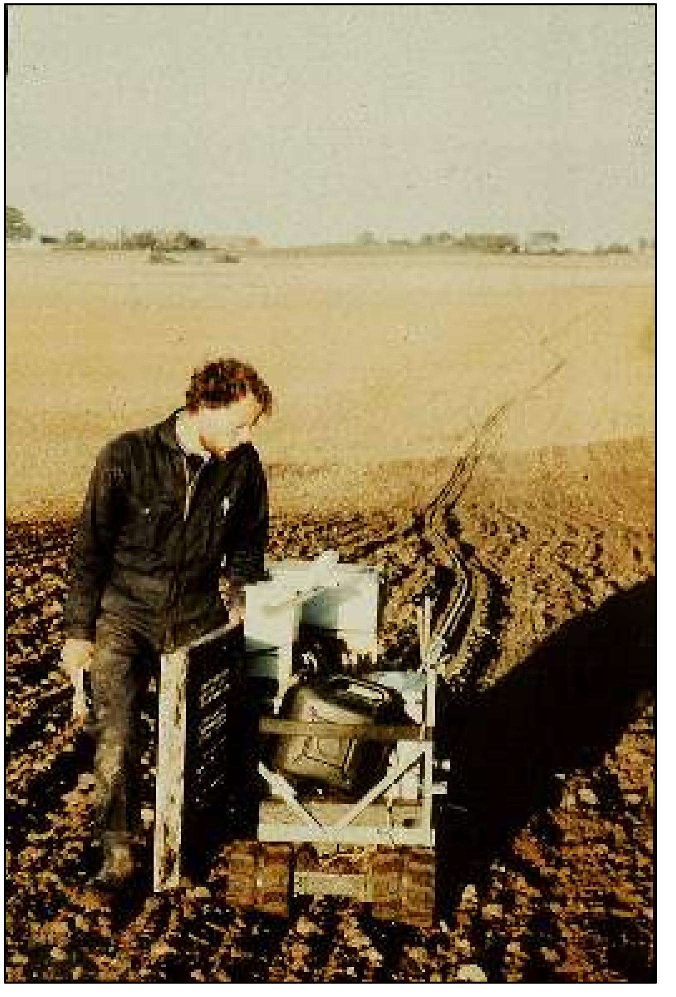
We can profile the subsurface by moving our array



The depth we are sensitive to will depend on the array configuration and the subsurface properties. For the array above we may assume that the apparent resistivity is at about half the electrode spacing.

The Pulled Array Continuous Electrical Profiling (PACEP) method was developed by the Aarhus hydrogeophysics group as a cost effective method for spatially dense measurement over large areas.

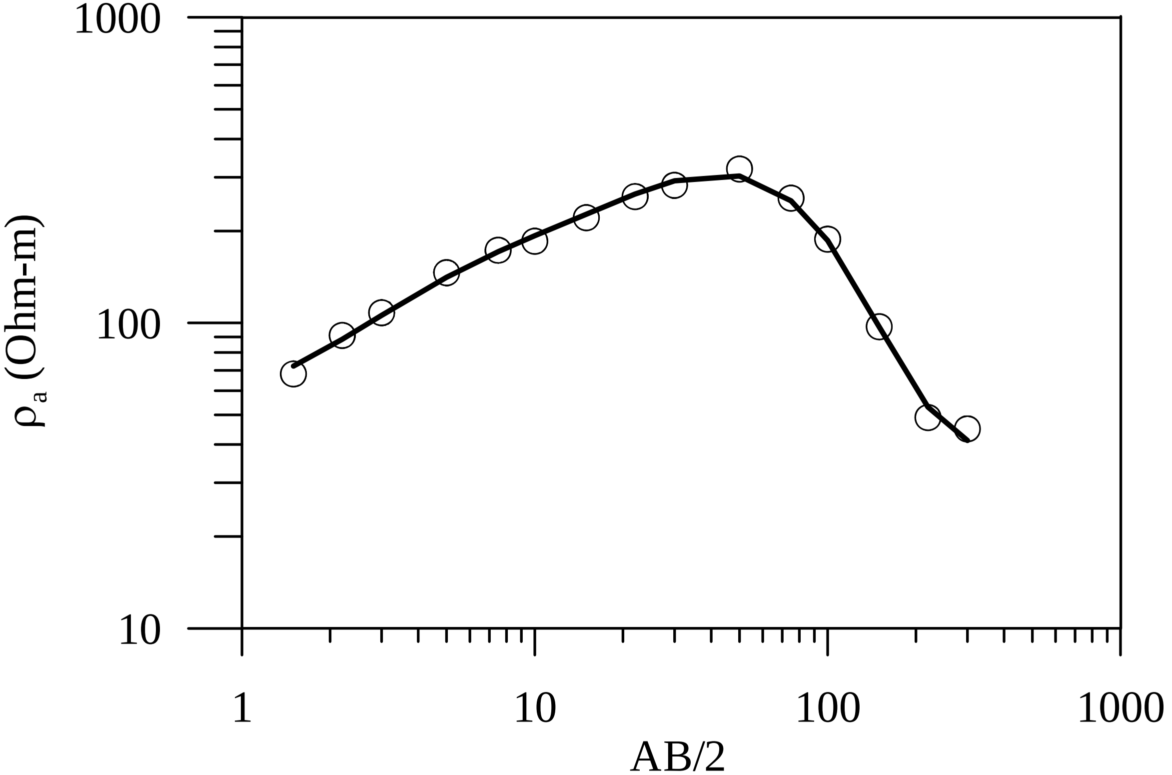
An electrode array is towed across the field behind a small vehicle and measurements with three sets of electrodes with different separations are performed continuously and simultaneously while actively towing the electrode array.



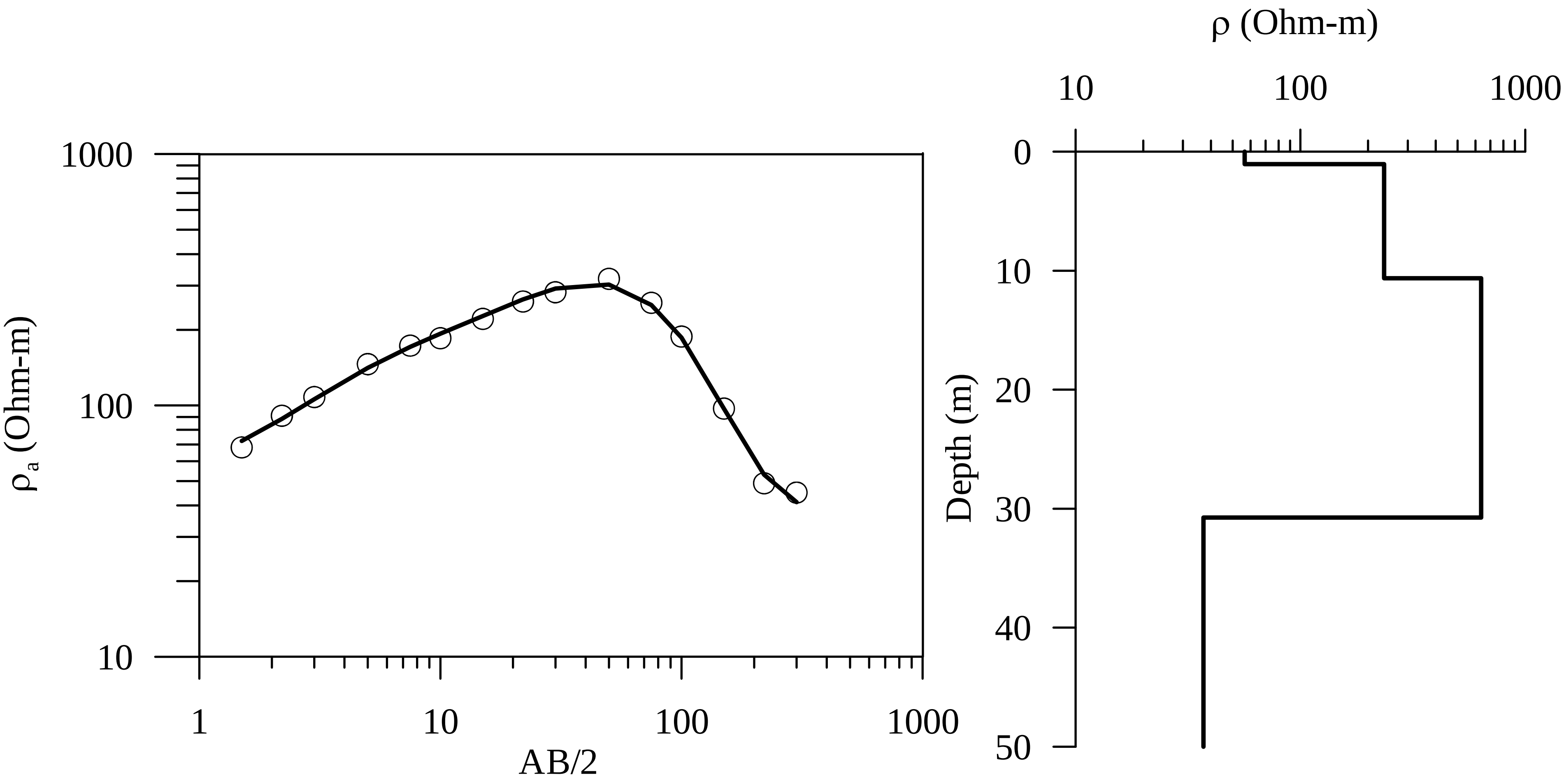
Resistivity soundings

Soundings - often called vertical electrical soundings (VES) – allow us to build up a 1D profile of the subsurface.

The array spread is progressively increased and the depth of sensitivity increases.



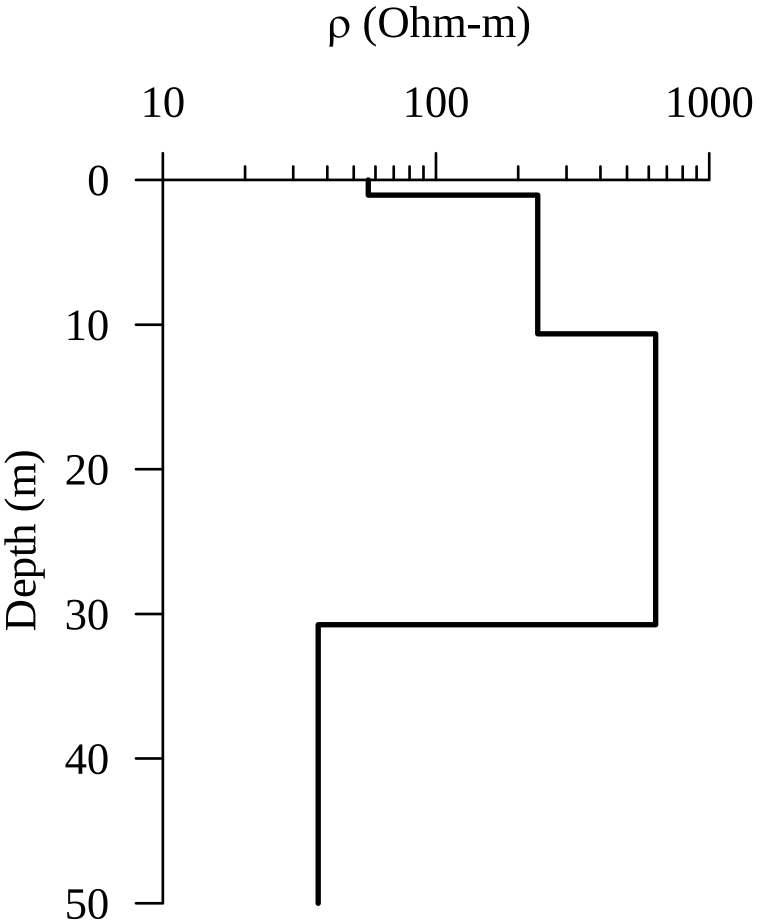
Inverse methods (see later) are then used to determine a 1D resistivity structure that best matches the data.



VES has been widely used in hydrological investigations to determine lithological boundaries.

The method has also been used to monitor dynamic processes, e.g. responses to recharges and travel times of pollutants.

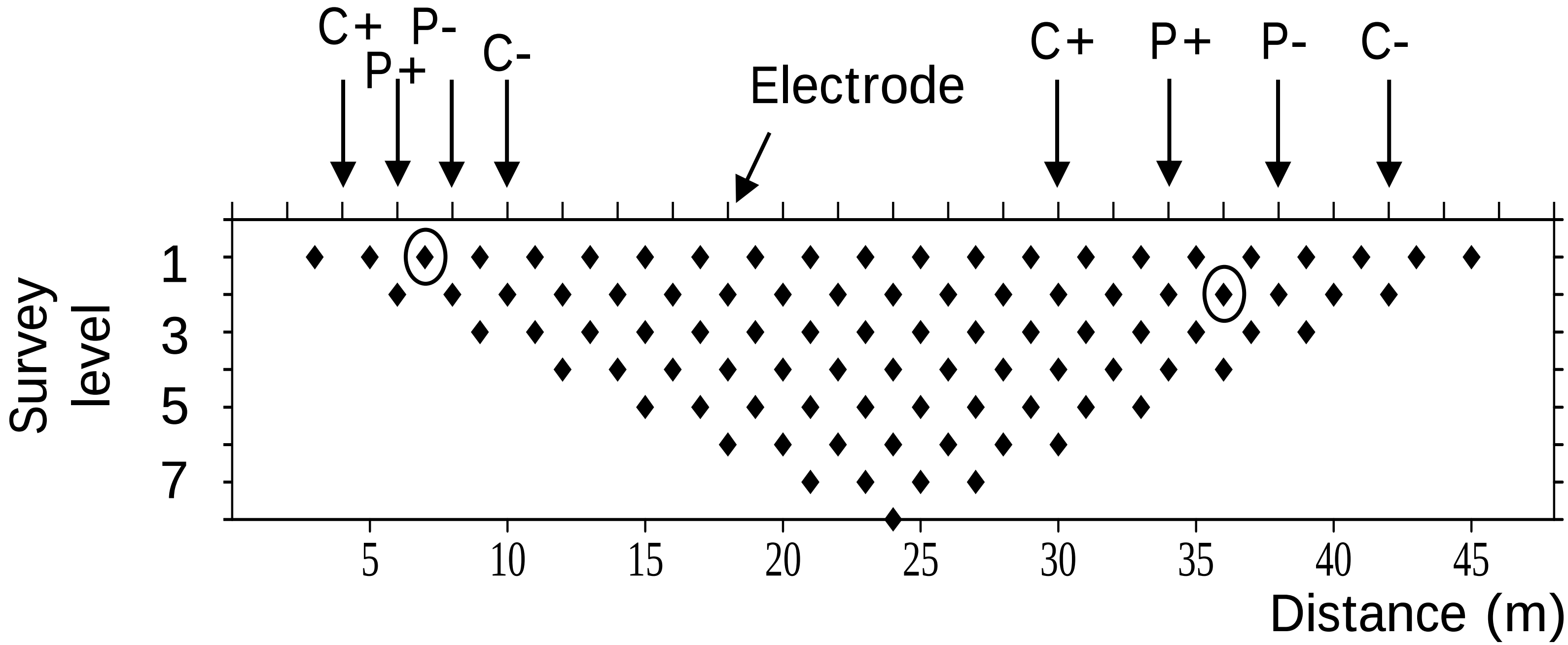
The approach is clearly limited if the 1D assumption is not valid.



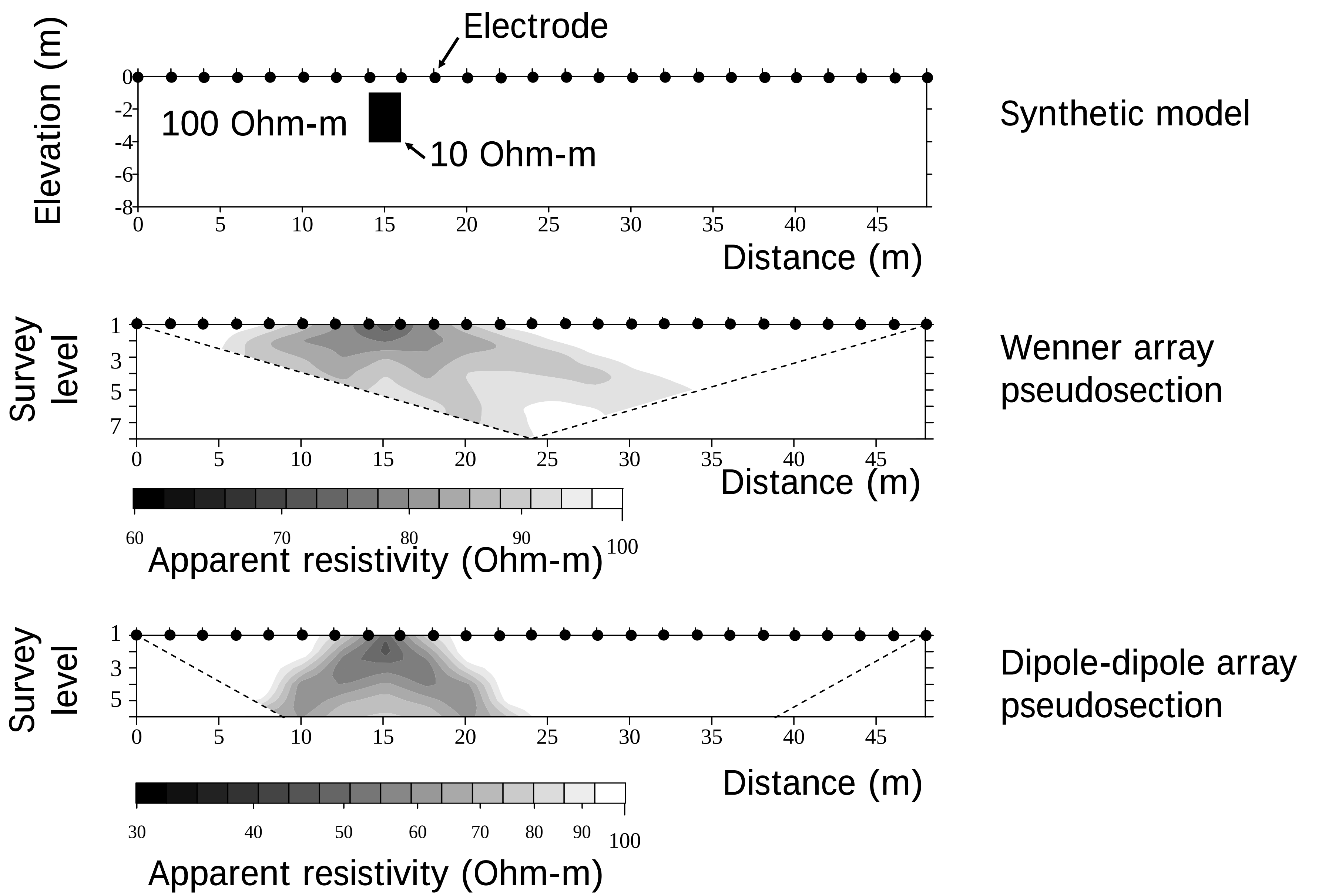
Resistivity surface imaging

Developments in multi-electrode instruments has led to widespread use of resistivity imaging.

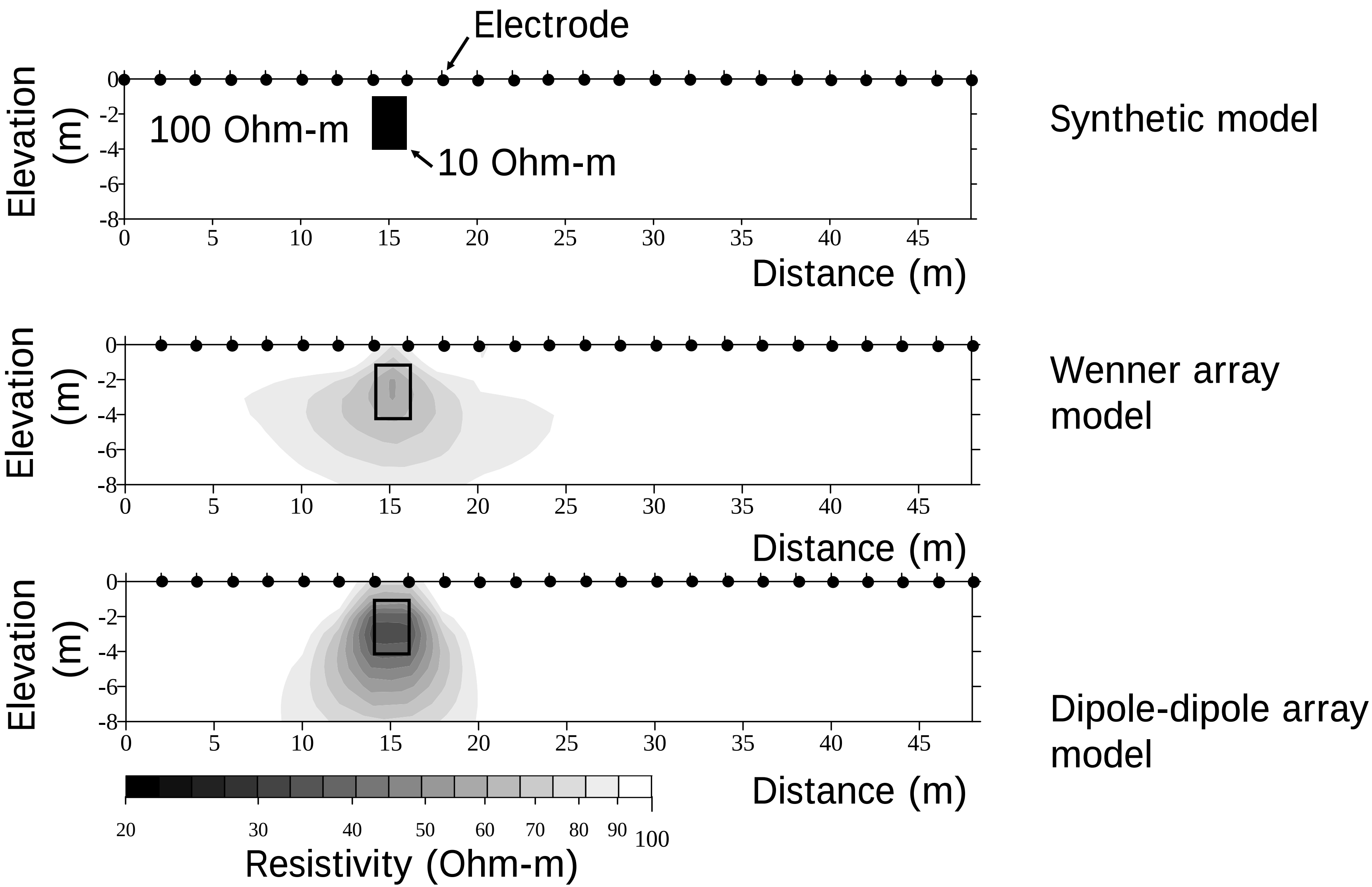
Here profiles are measured at different electrode separations (i.e. different survey depths).



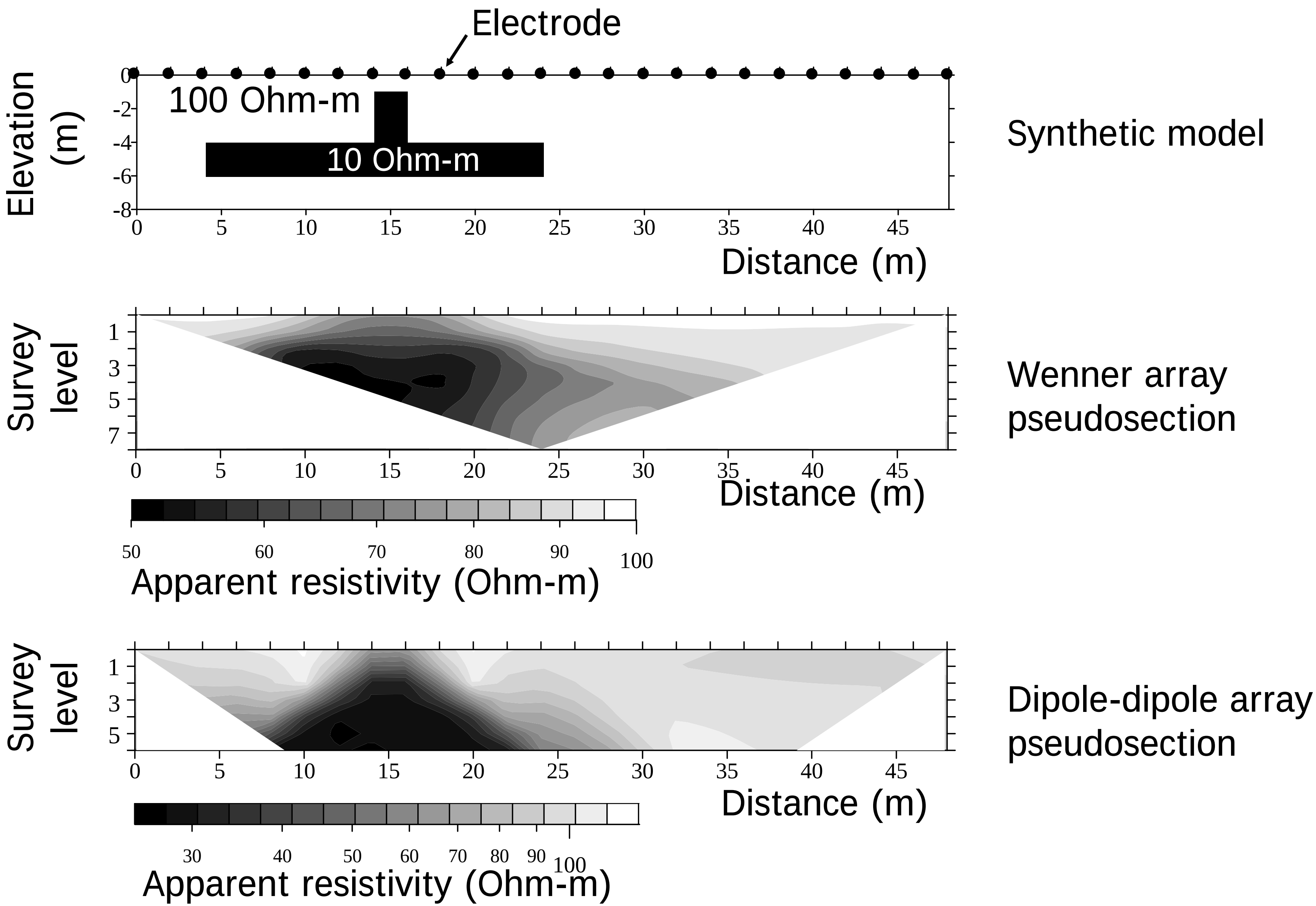
A *pseudosection* is built up using measured apparent resistivities



These data may be inverted (see later) to determine a resistivity image that is consistent with the data



Note that the pseudosection doesn't always show a structure that resembles the subsurface.



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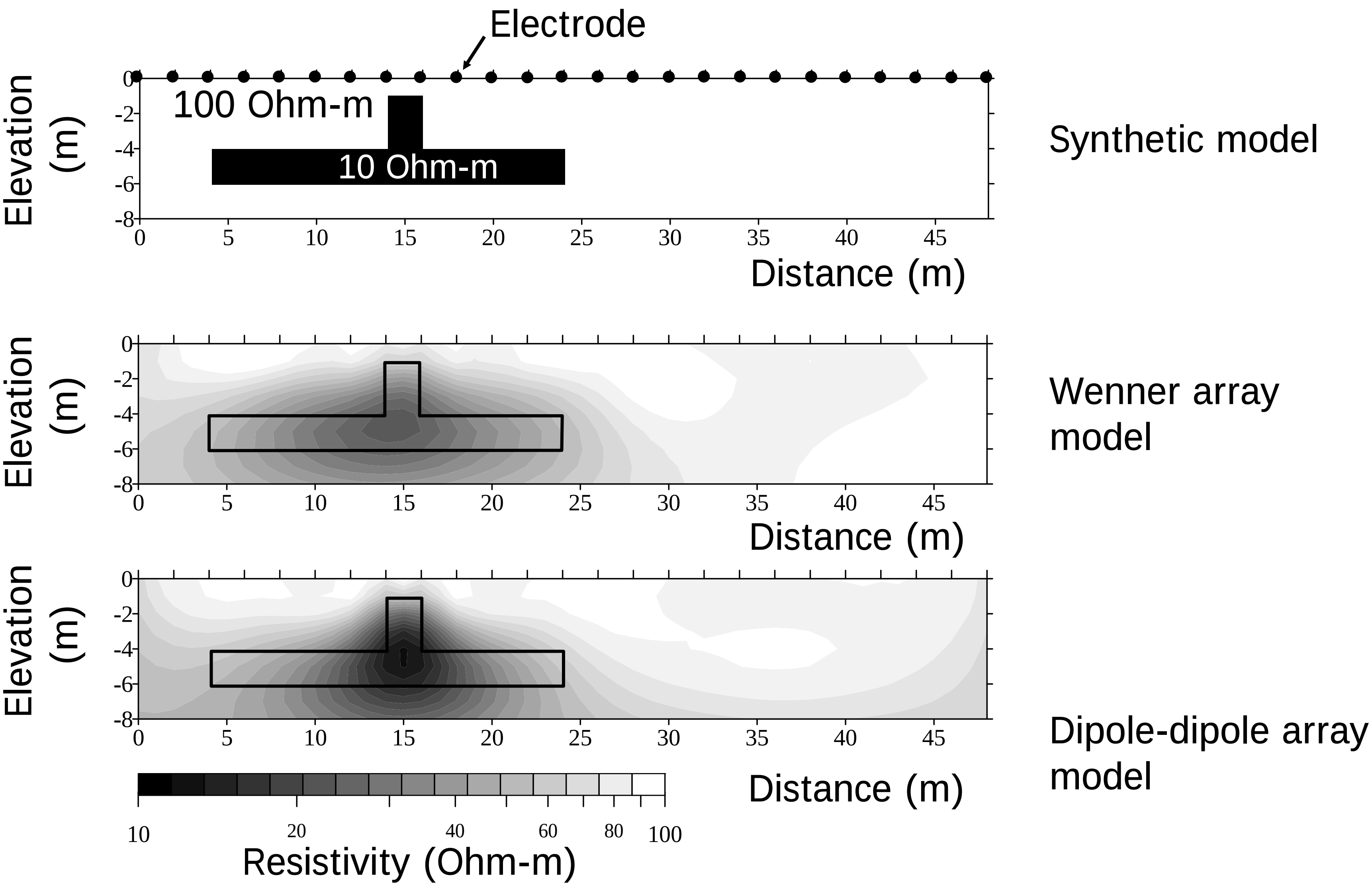
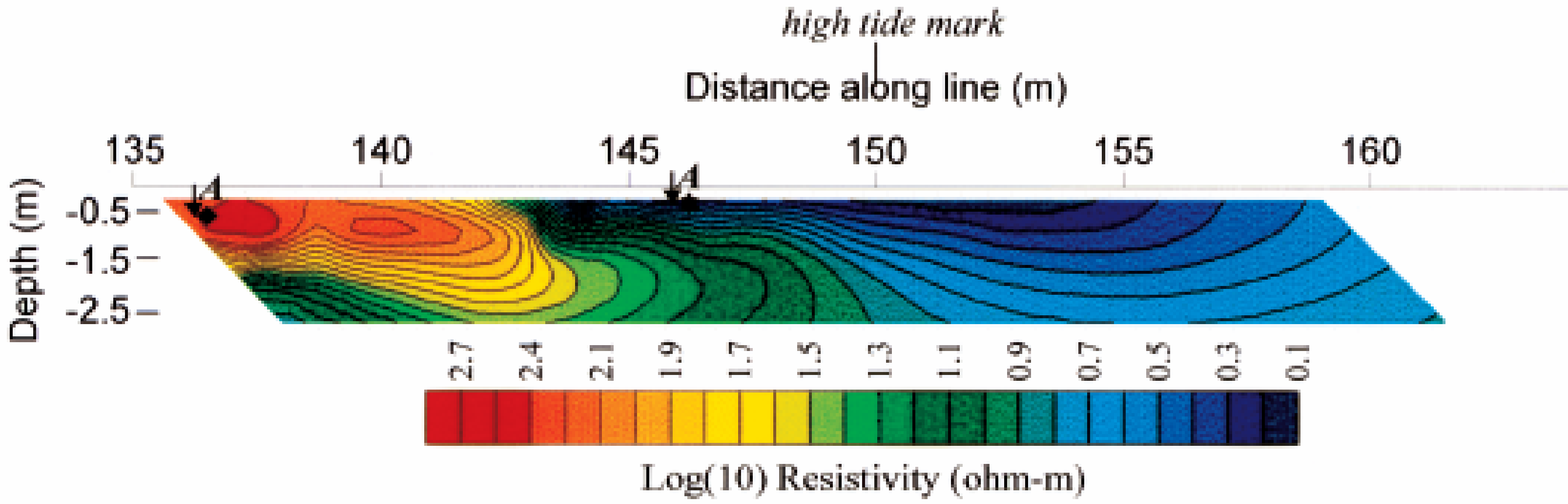
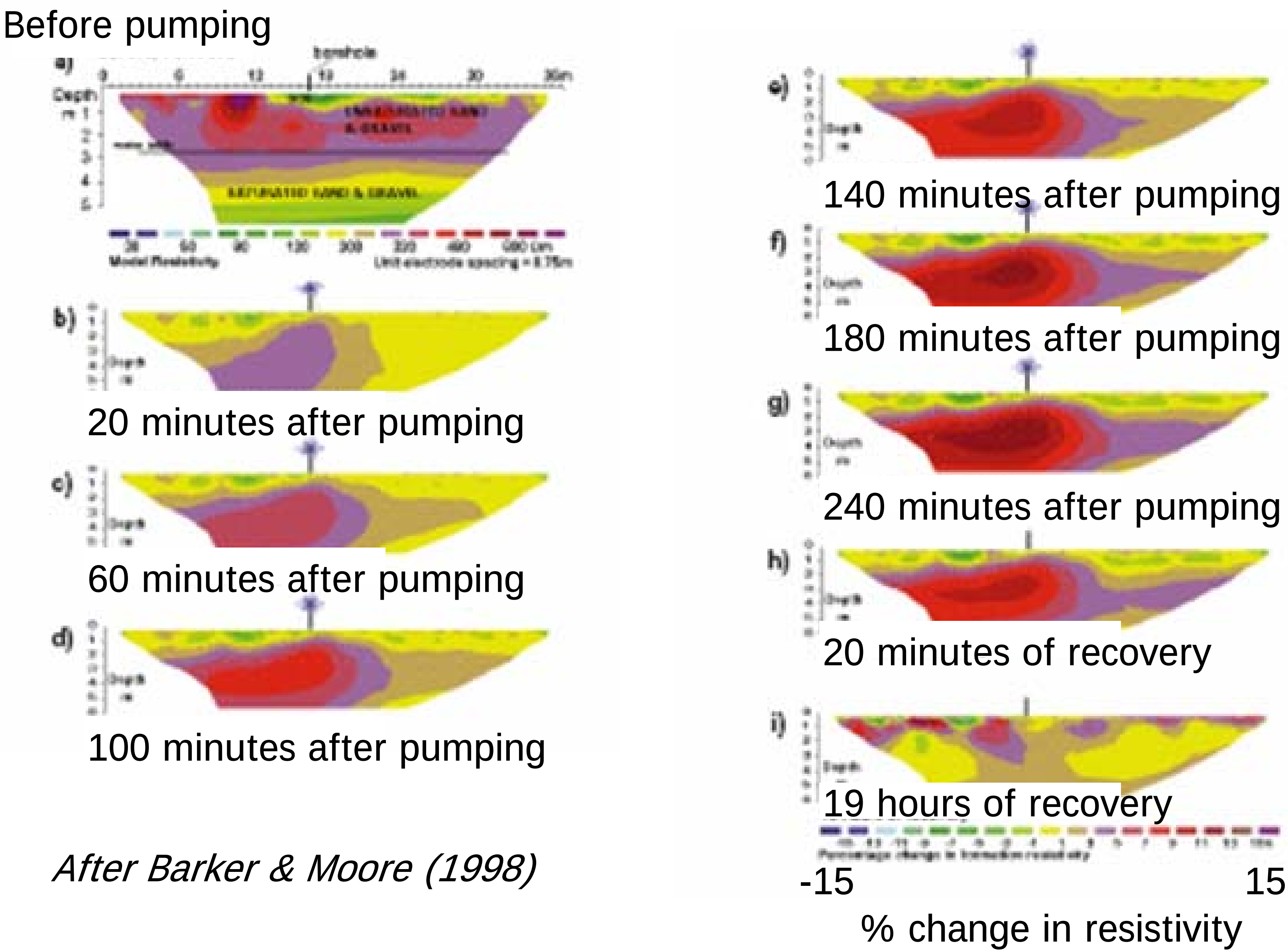


Surface resistivity imaging has been used widely to look at subsurface structure and dynamic processes



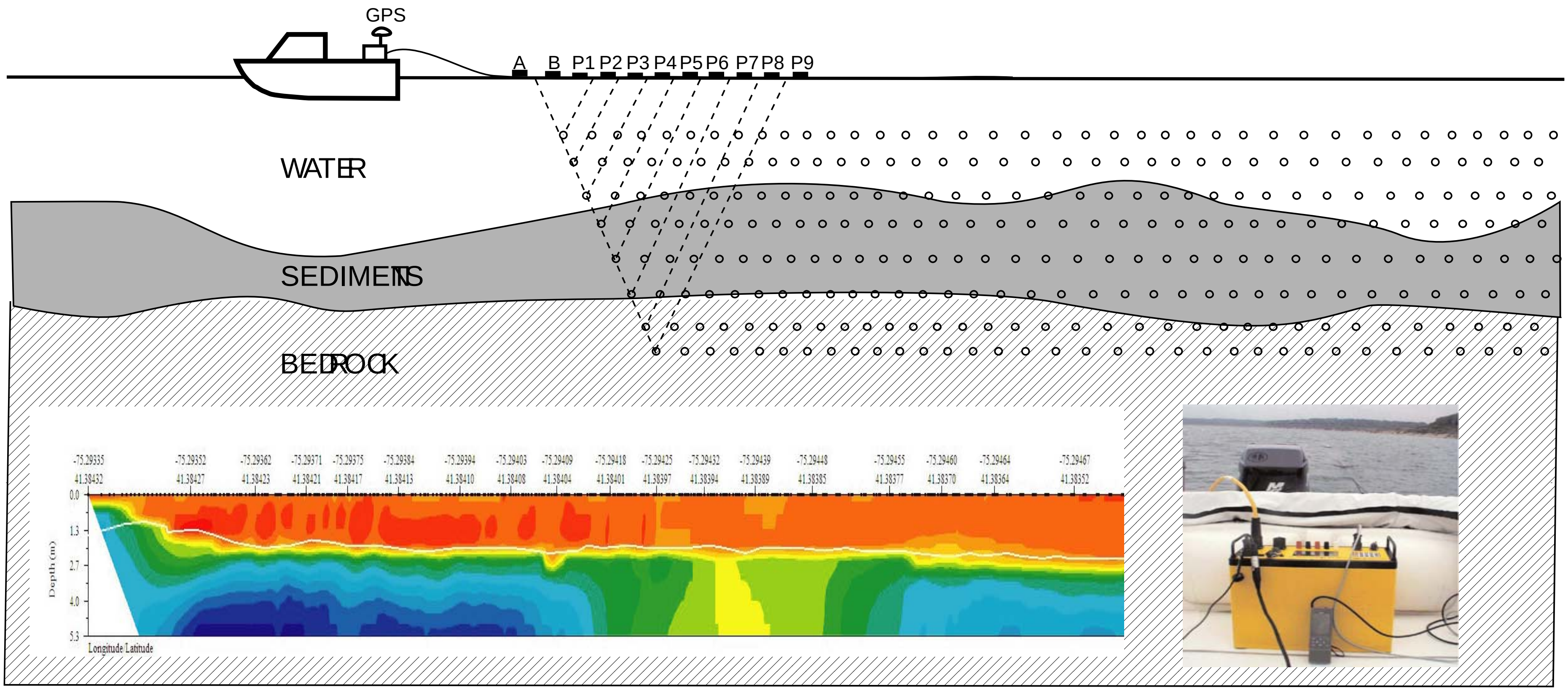
After Slater and Sandberg (2000)

Surface resistivity imaging has been used widely to look at subsurface structure and dynamic processes

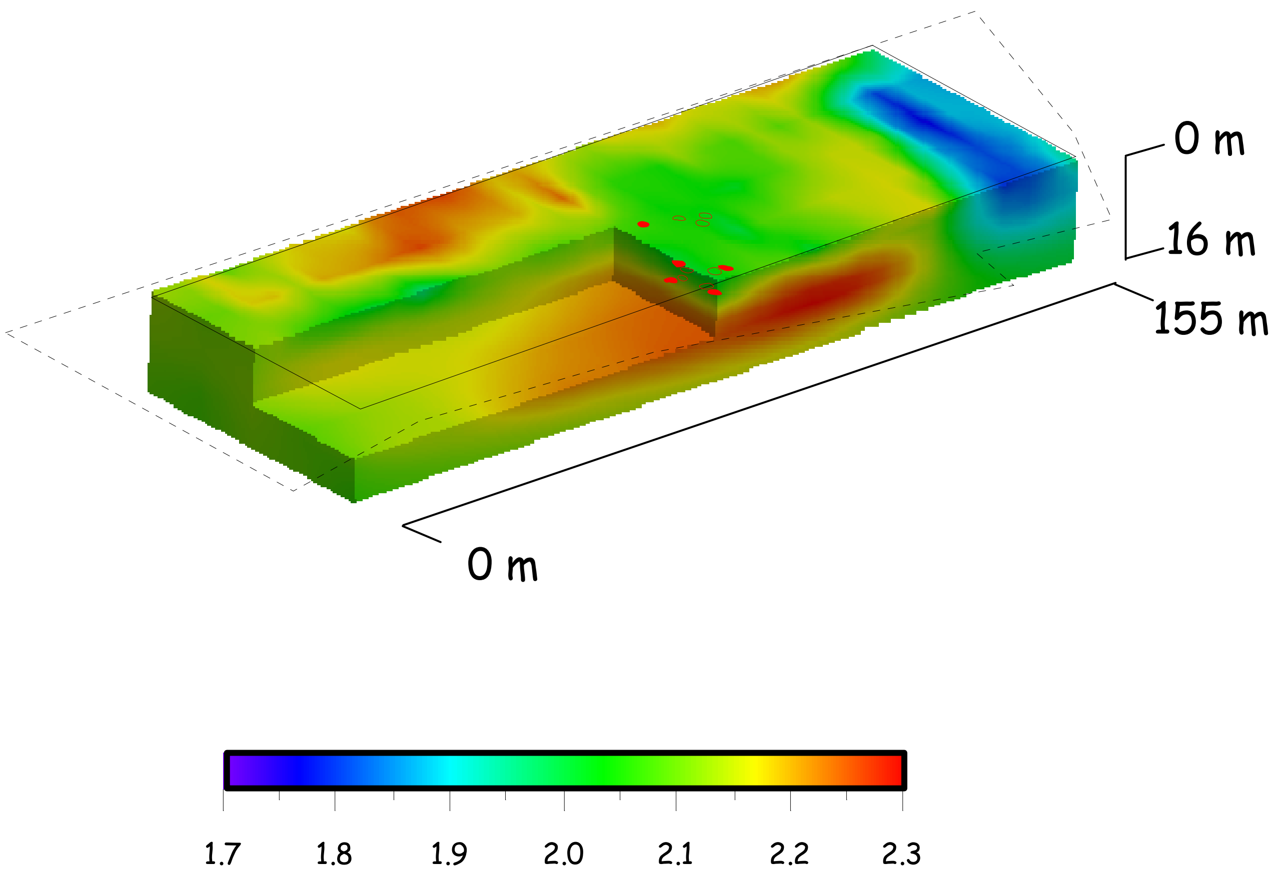


After Barker & Moore (1998)

Surface resistivity imaging based on continuous surveys have been developed for land and marine investigations



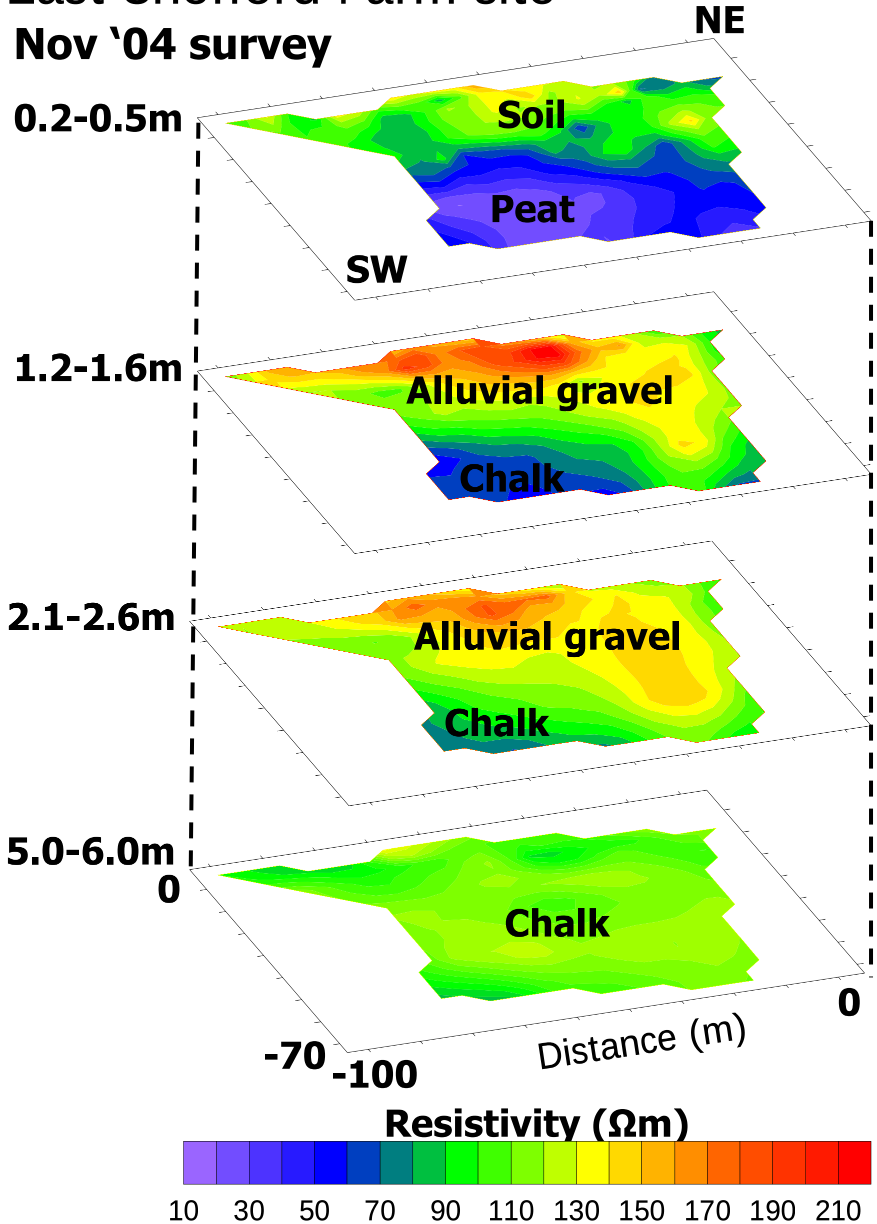
Multiple 2D or true 3D data can be used to show subsurface structure ...

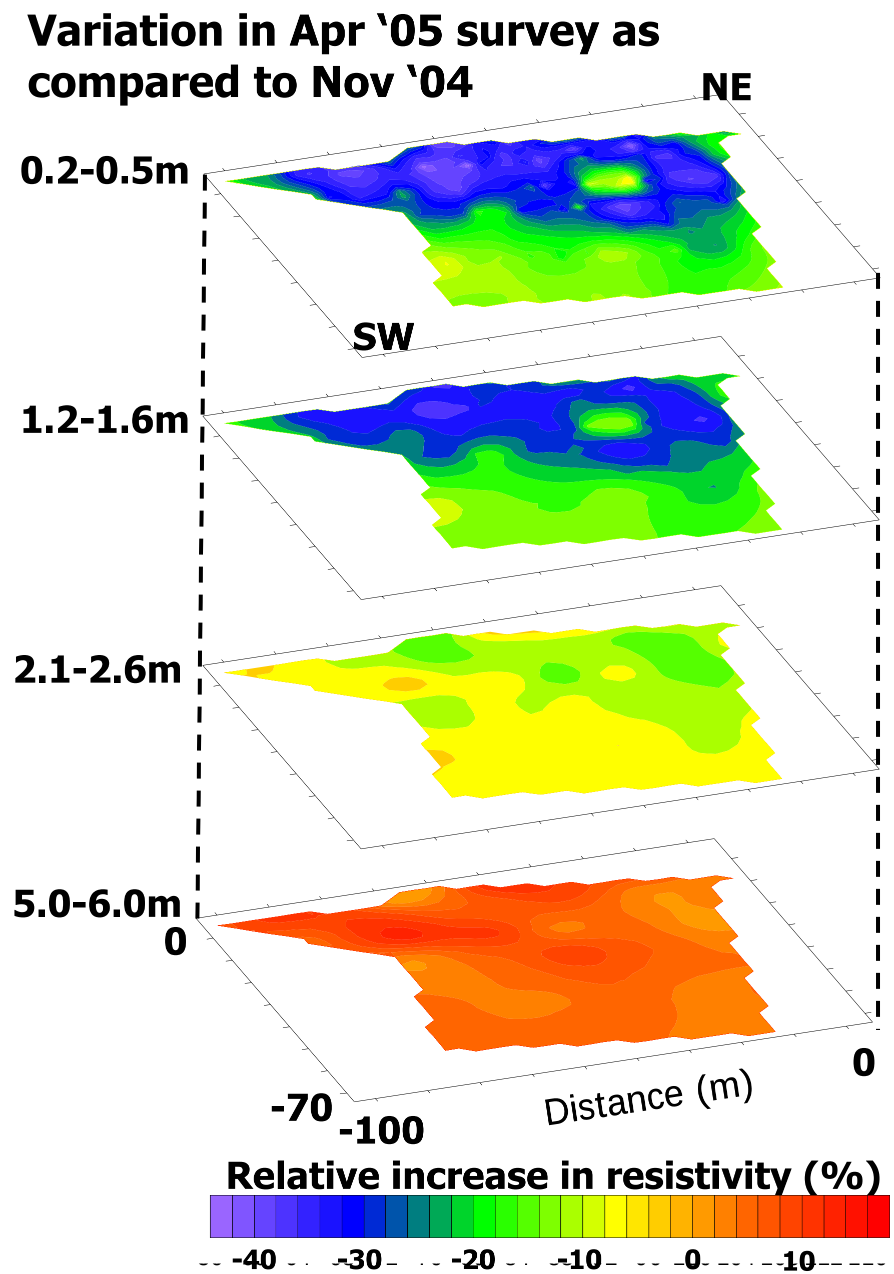


$\log_{10}$ resistivity in Ohm-m

... and changes over time in 3D

East Shefford Farm site





Resistivity data acquisition issues

Data collection speed will depend on:

Number of channels (detectors),

Source frequency,

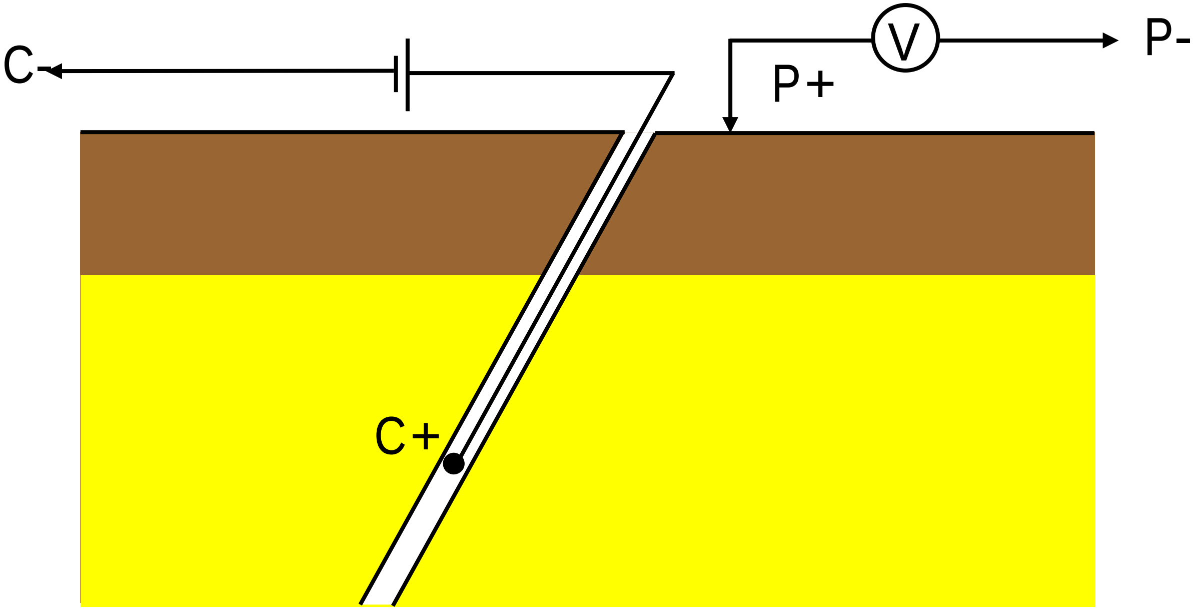
Stacking requirements

Basic (single channel) systems may only be capable of around 400 to 500 measurements per hour. Some multi-channel systems can work at around 2000 measurements per hour or faster.

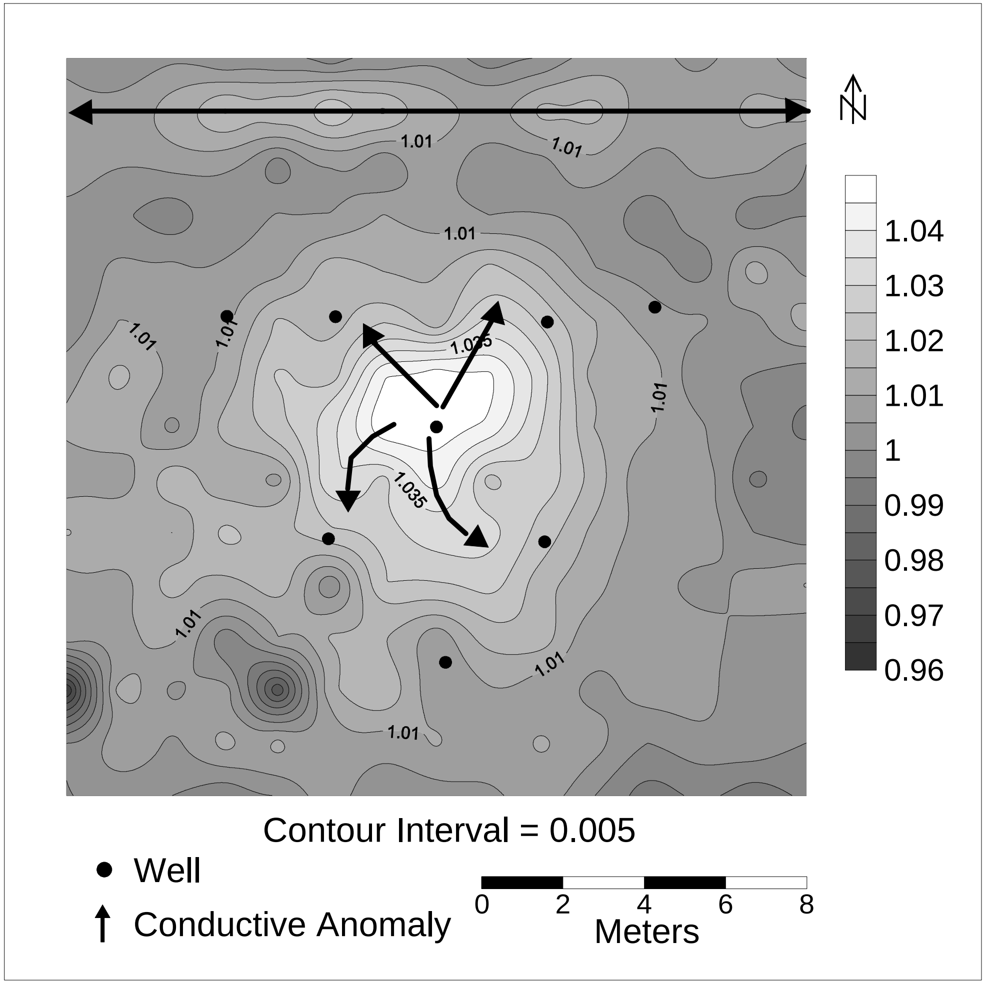
Resistivity single borehole surveys

To gain better resolution at depth we may use electrodes in boreholes.

These can be in single boreholes, e.g. mise-à-la-masse ...



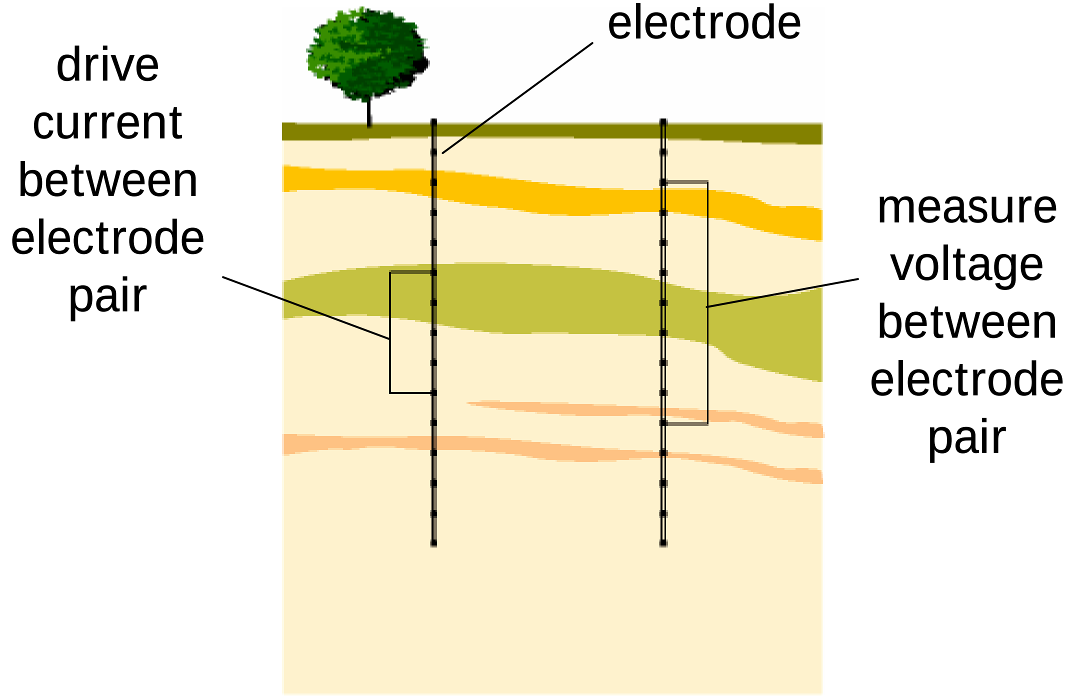
Nimmer(2005) used mise-à-la-masse to study tracer migration in fractured basalt. She also used enhanced the survey by using borehole electrodes for potential measurements.



Resistivity cross-borehole imaging

Electrodes in two (or more) boreholes can also be used to gain maximum resolution – *cross-borehole electrical resistivity tomography (ERT)*

Stainless steel mesh, copper and lead are common electrode materials.



Resistivity cross-borehole data acquisition issues

Low cost systems developed for surface imaging may be used for cross-borehole work but some suffer from:

Single channel (slow),

Poor dynamic range (limited application),

Constant current source (limited control)

Electrodes need to have contact with the soil/rock and the medium allowing this contact should resemble (electrically) the native soil/rock.

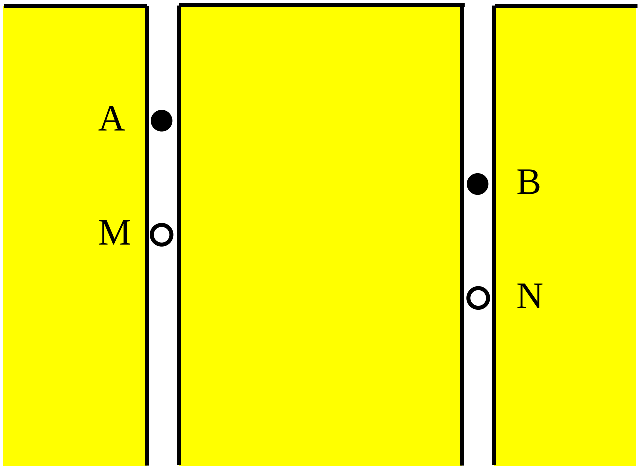
Below the water table electrodes may be temporarily installed in open holes or inside slotted plastic cased wells. In such cases inflatable packers may be used to prevent current flow along the borehole conductive fluid

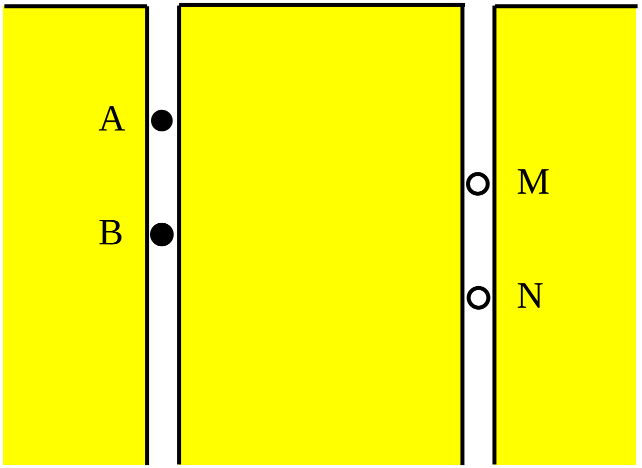
Above the water table electrodes are normally permanently installed.

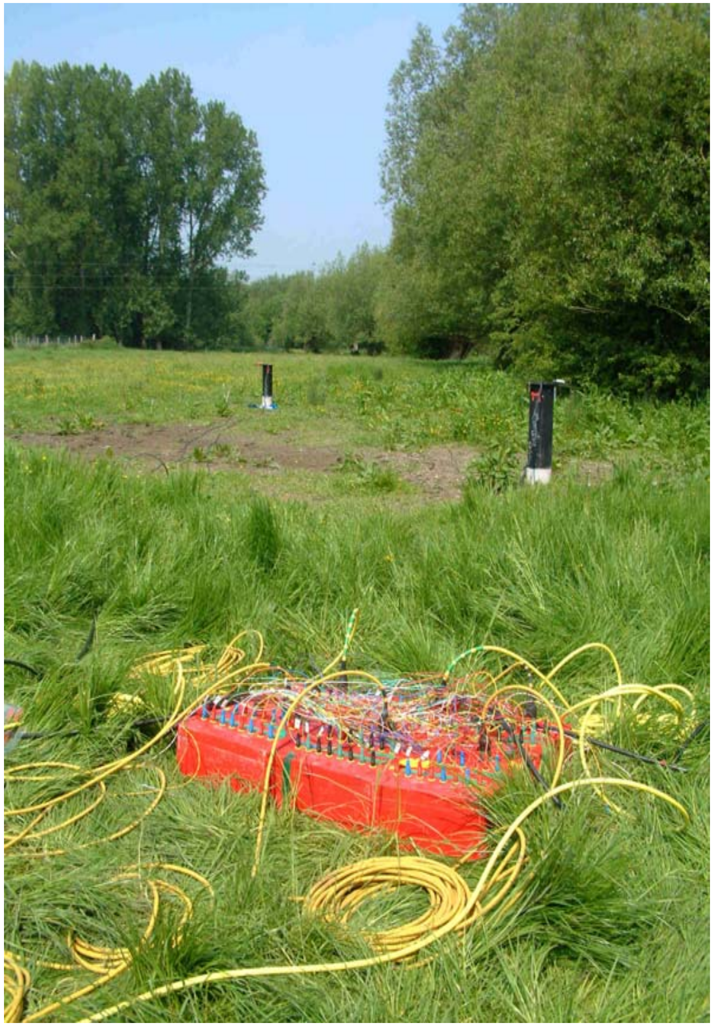
Pushed holes in unconsolidated sediments minimise electrode effects.

If drilled holes do not collapse backfill is required - typically drill returns or sand but avoid Bentonite.

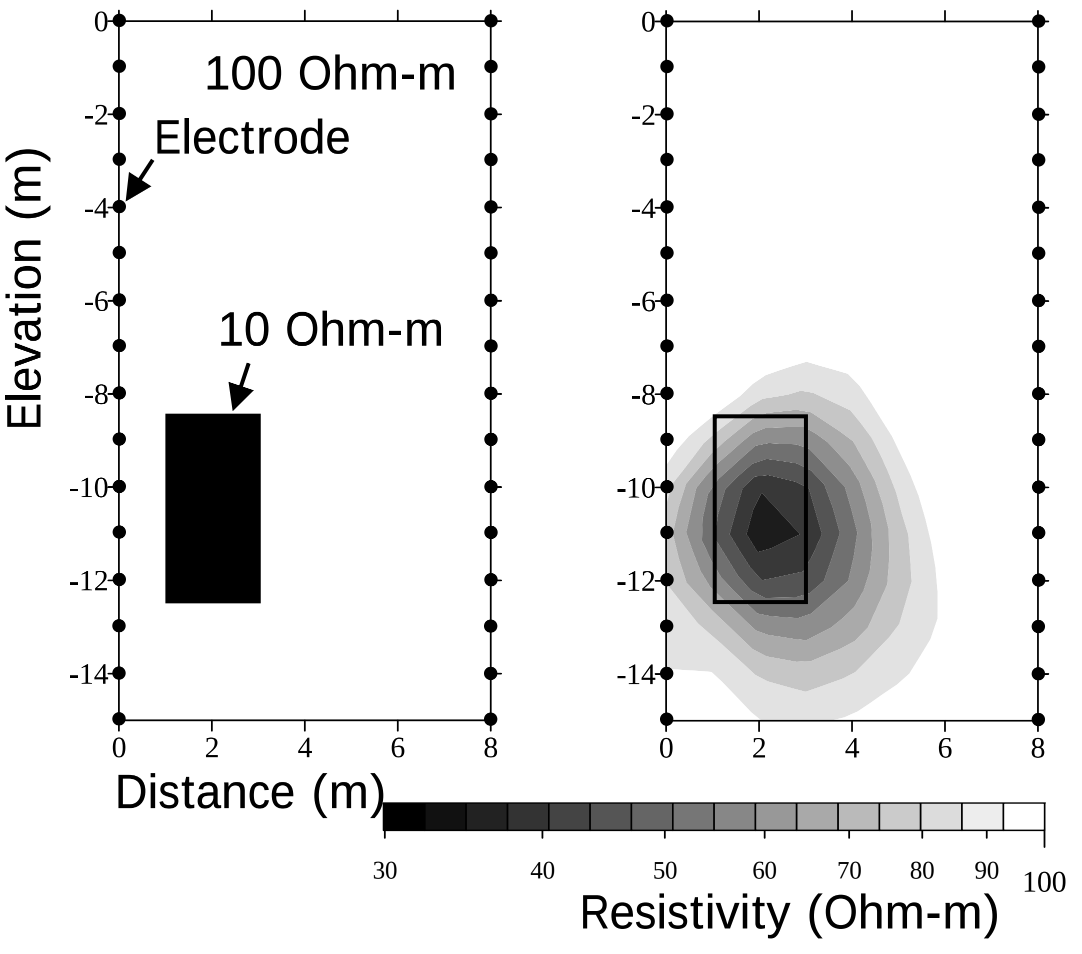
Many different types of measurement schemes are possible



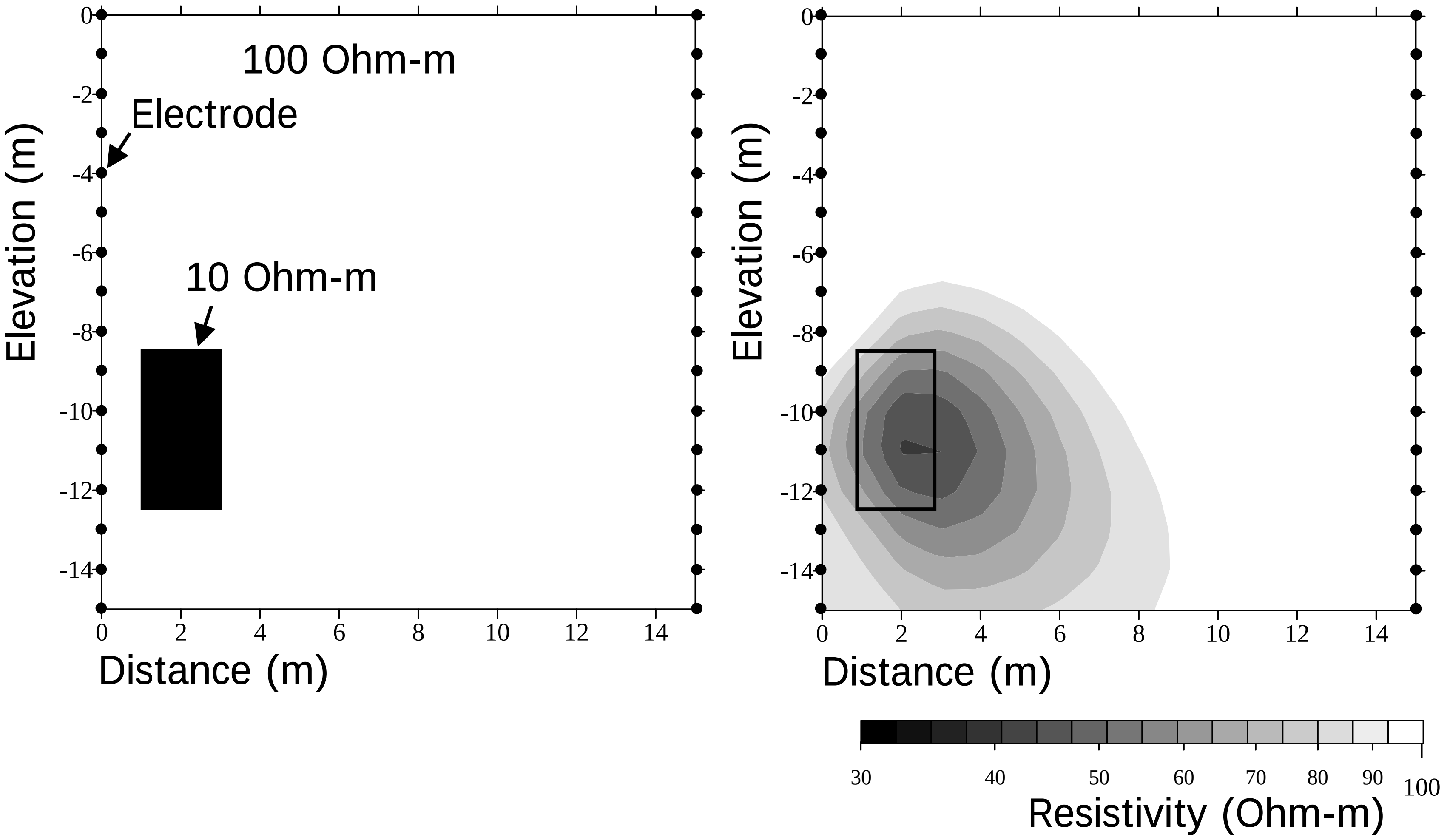




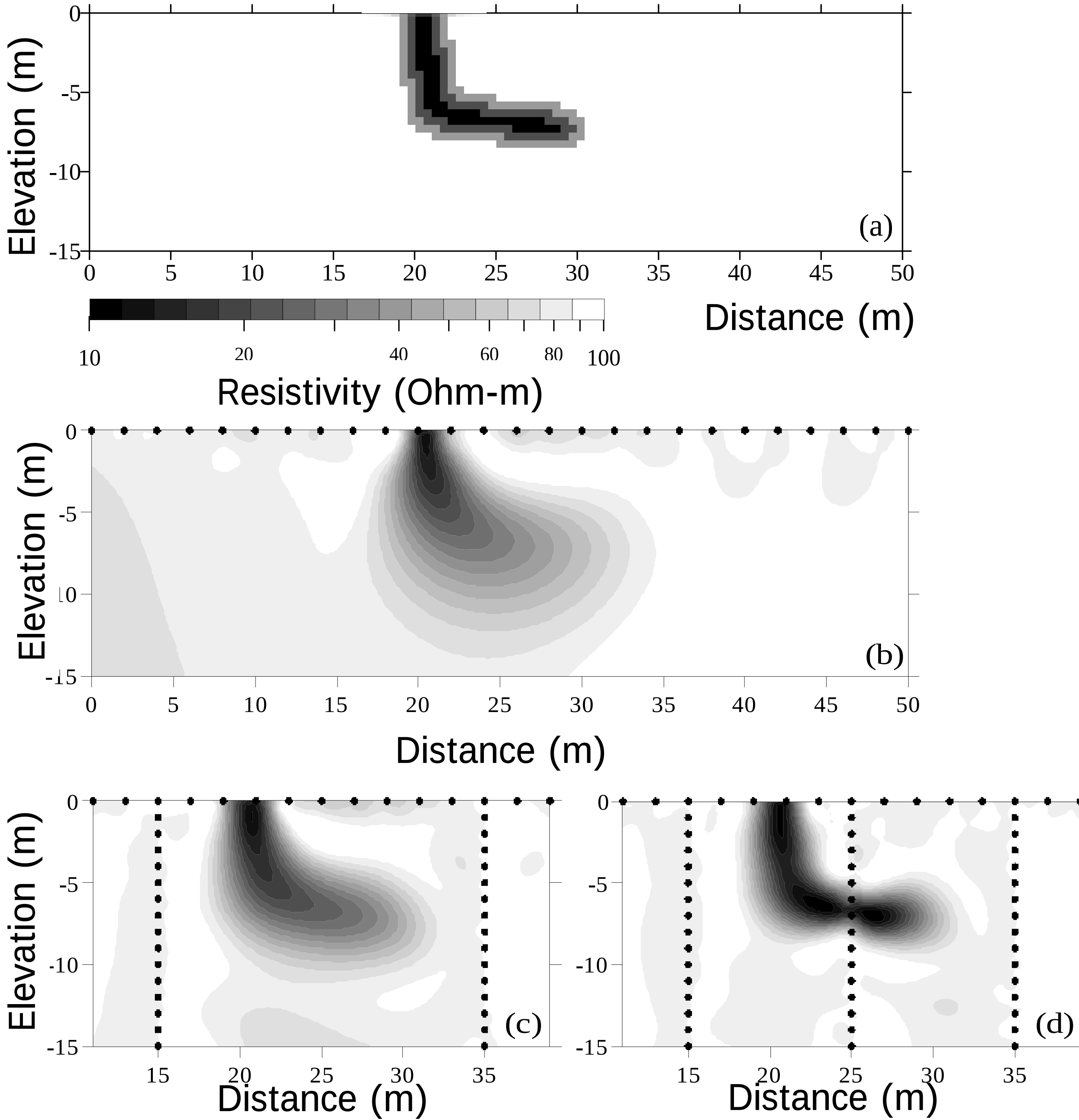
We can't build up pseudosections like in surface imaging but can invert data in the same way to get a model that is most consistent with the data



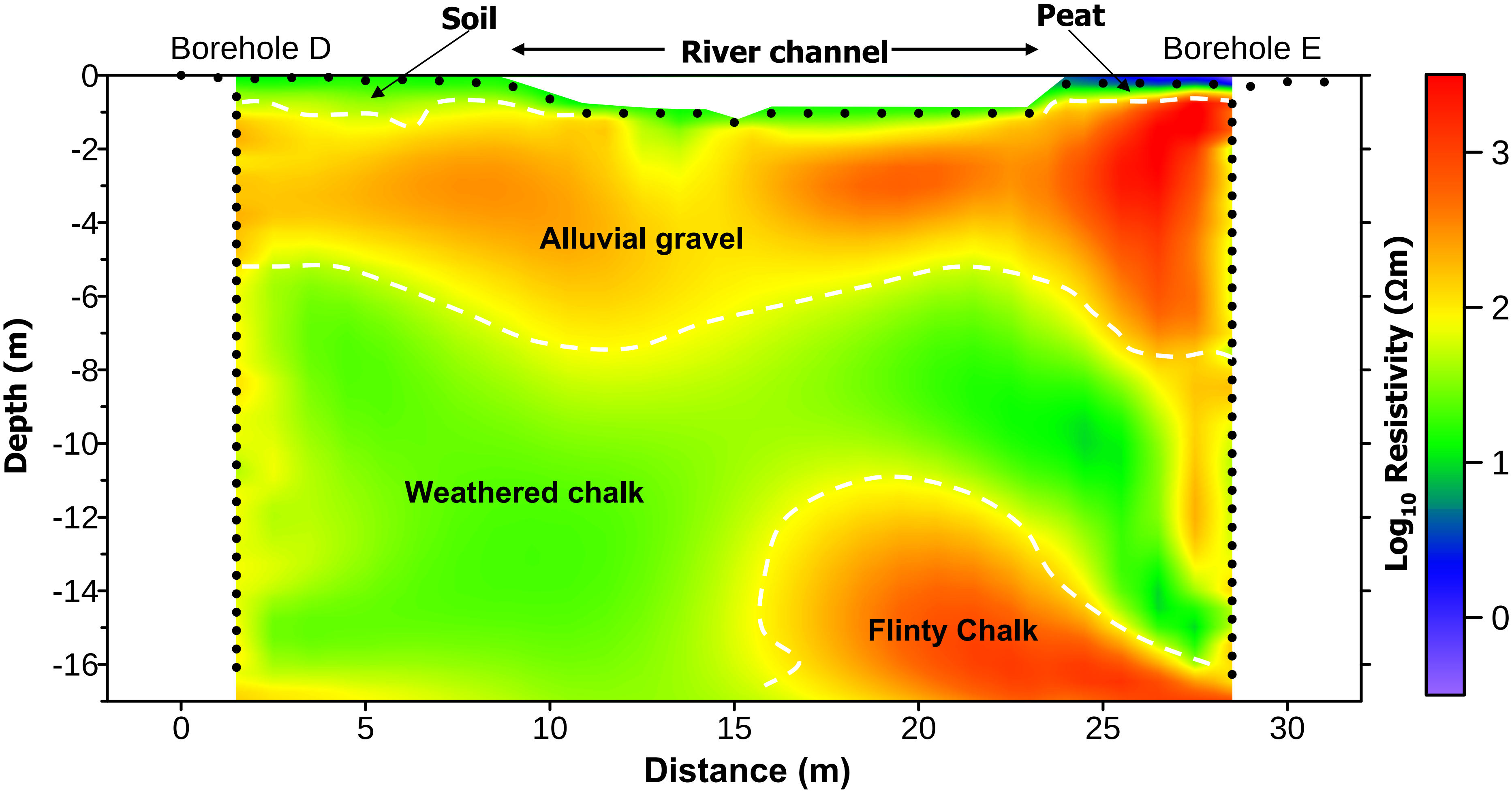
We have to be careful about borehole spacing since we loose sensitivity away from the boreholes



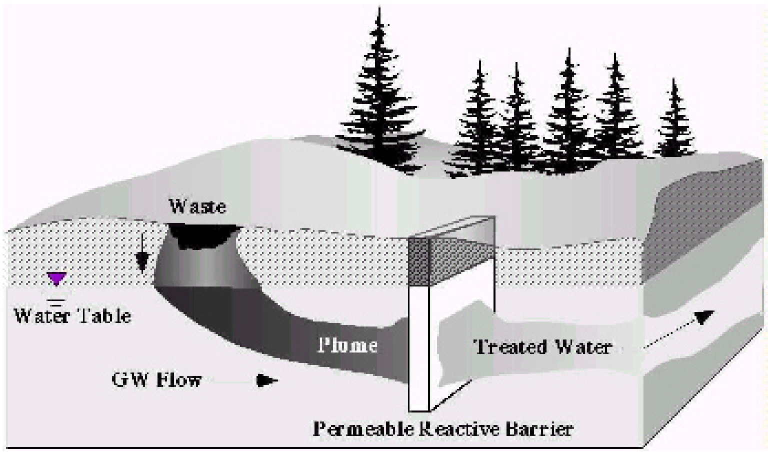
In some cases a combination of arrays is more suitable

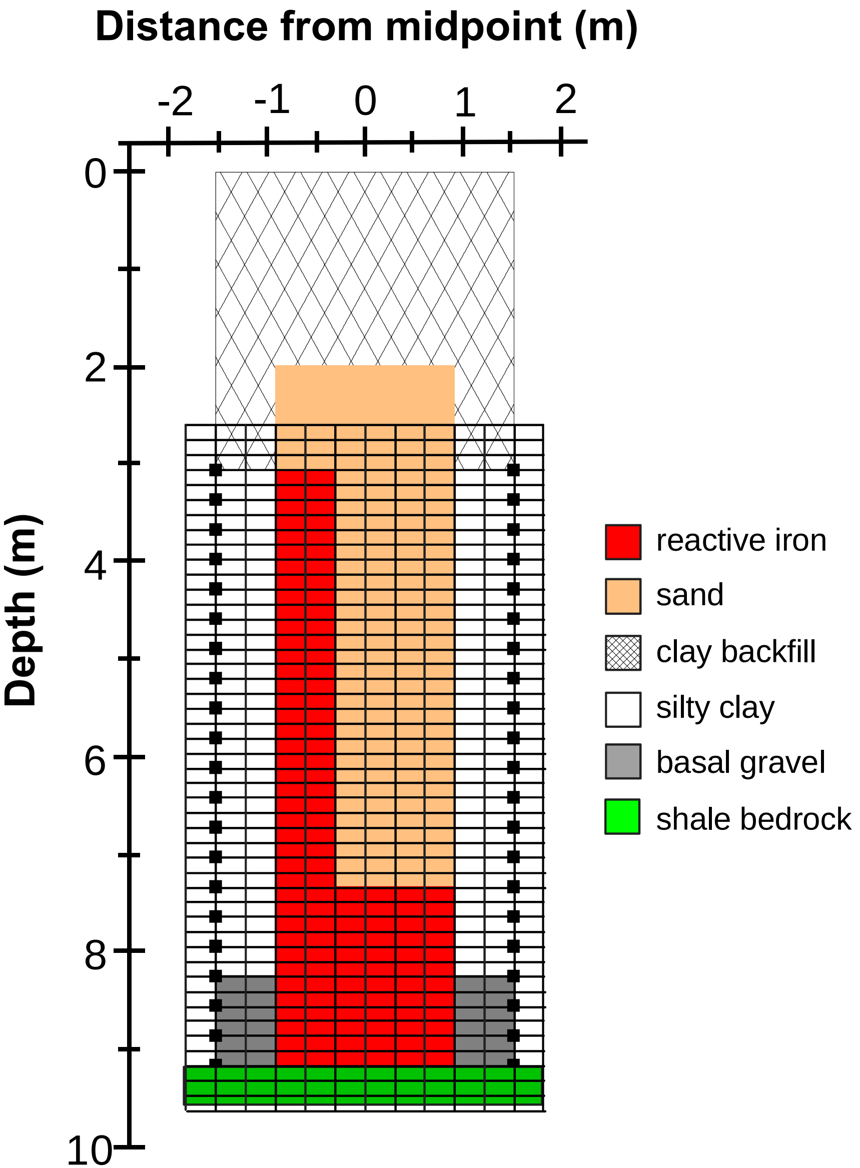


Example application to study subsurface structure beneath a river channel

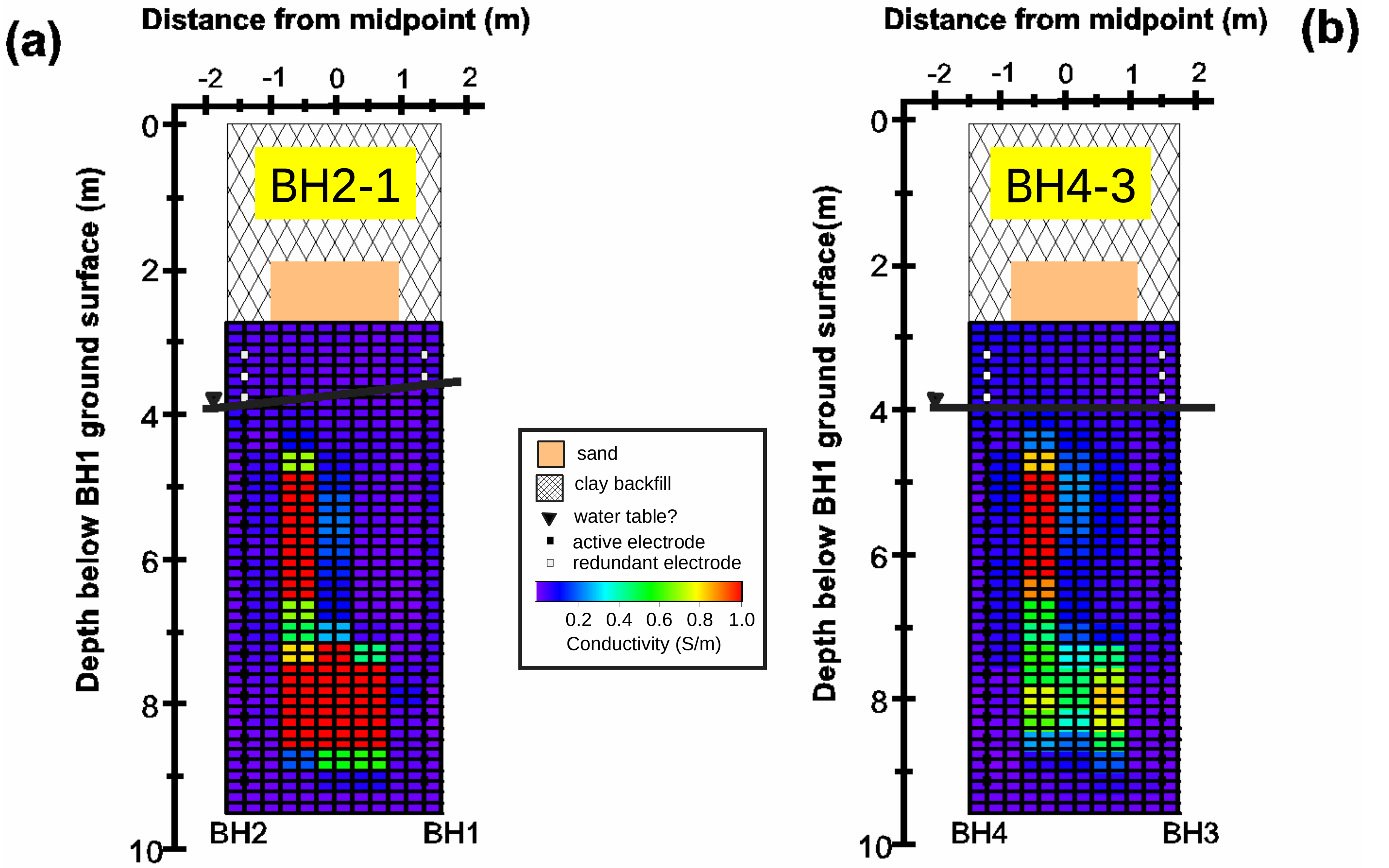


Cross-borehole imaging of permeable reactive barriers



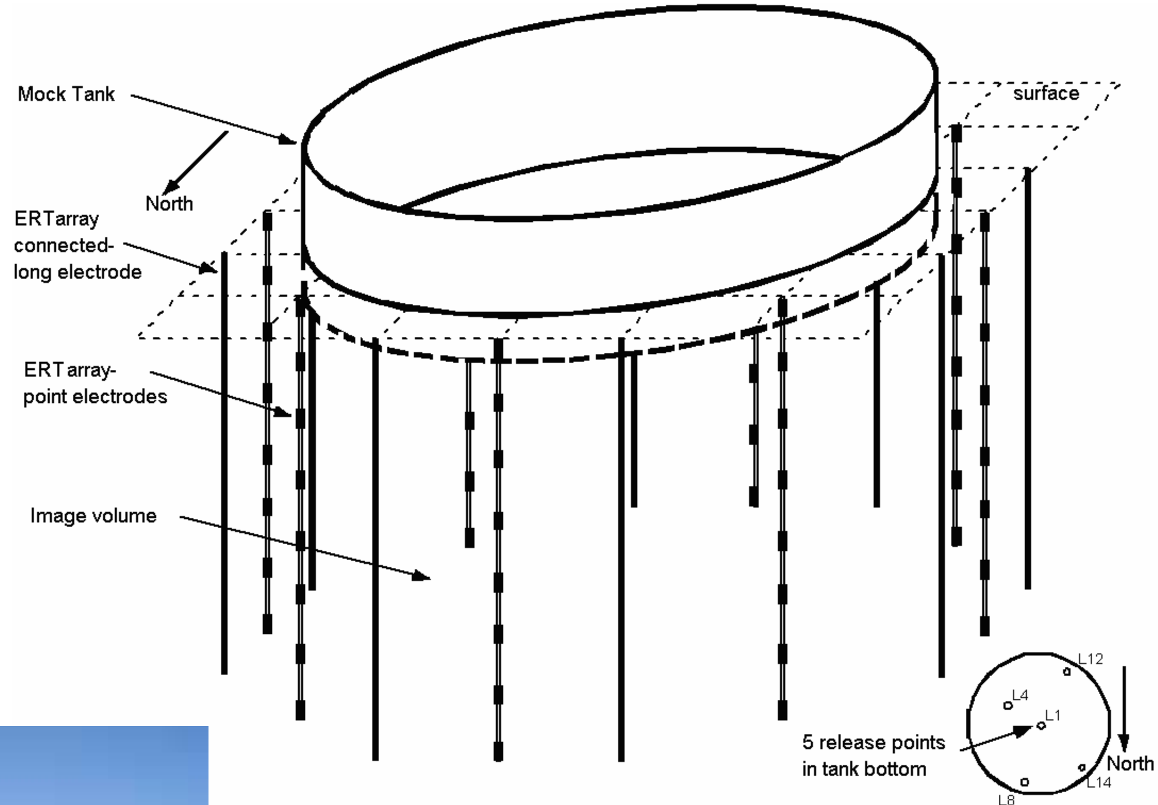


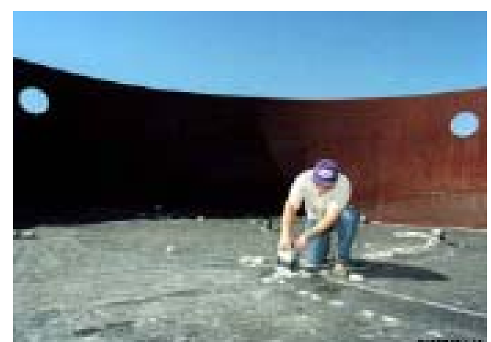
Cross-borehole imaging of permeable reactive barriers



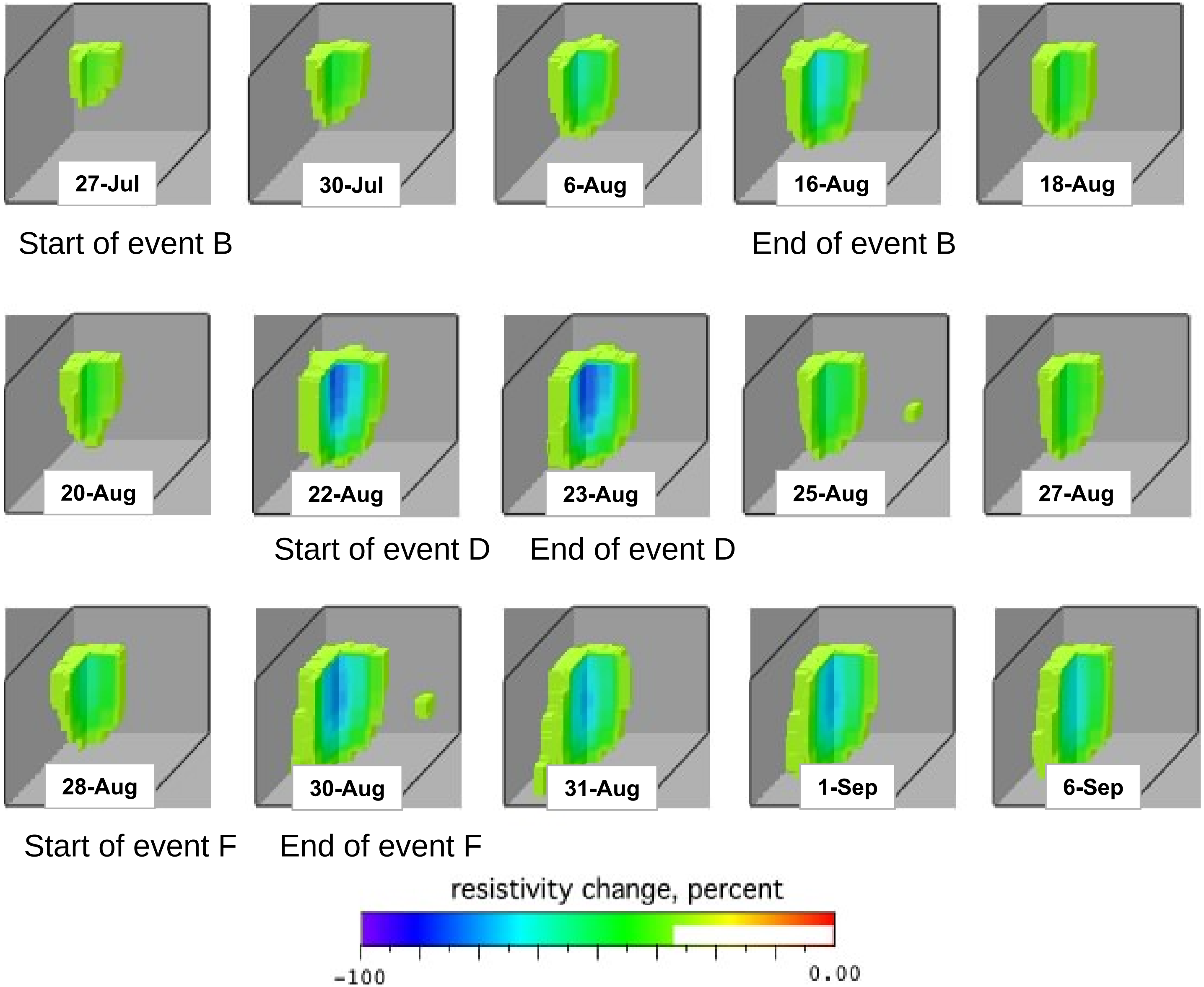
After Slater and Binley (2003)

Monitoring leakage into the vadose zone at Hanford





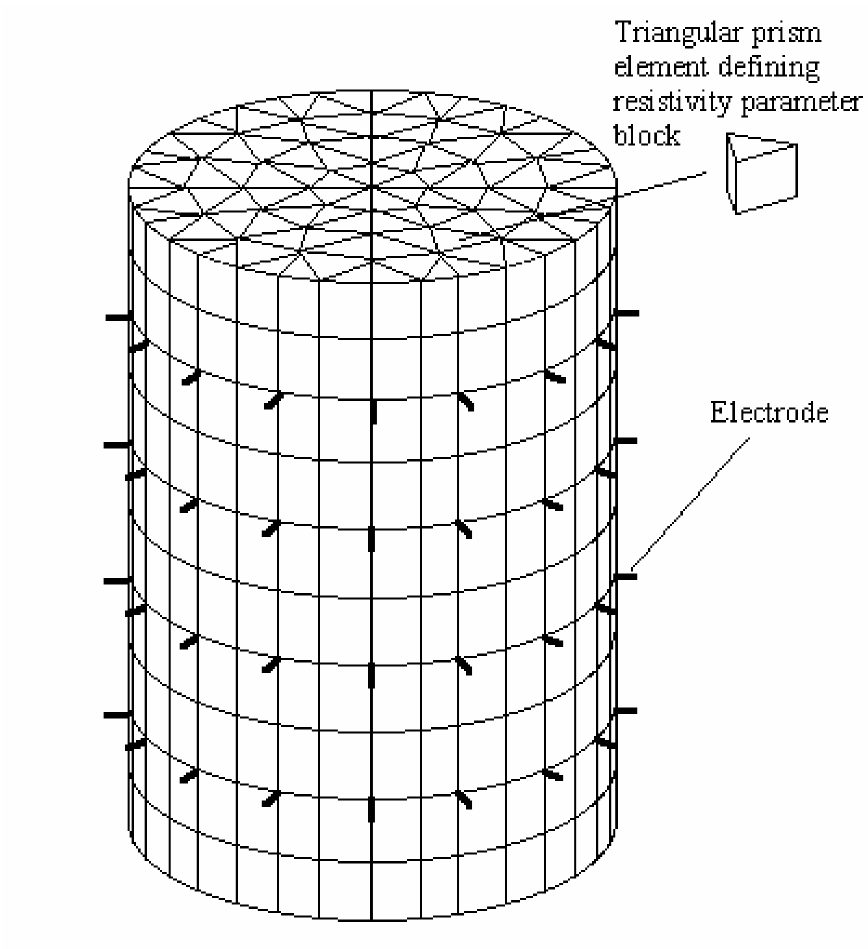
Monitoring leakage into the vadose zone at Hanford

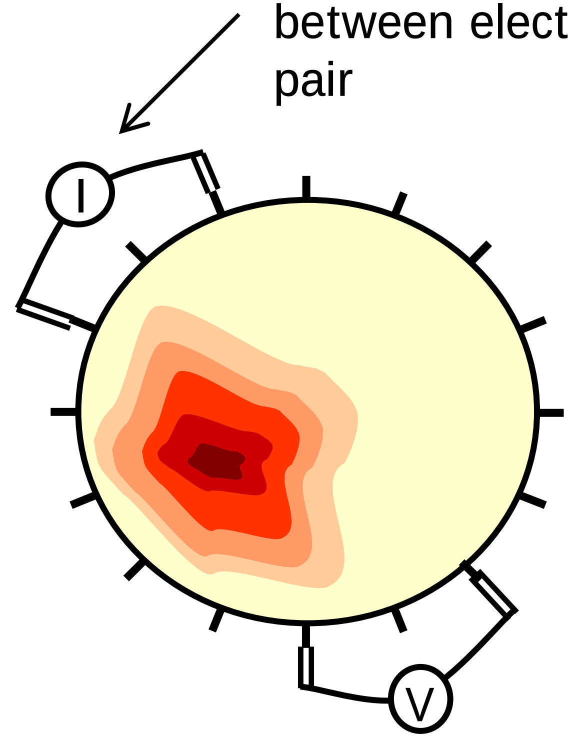


After Daily, Ramirez and Binley (2004)

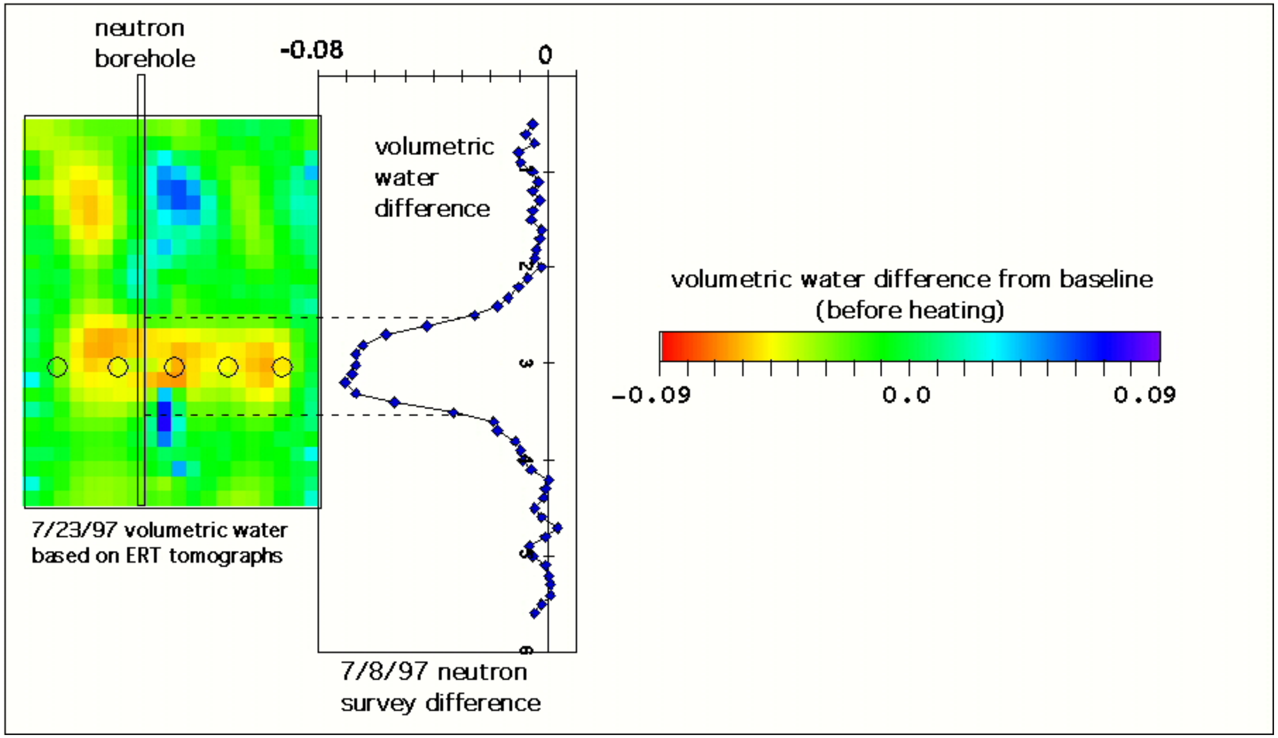
Resistivity core and block imaging

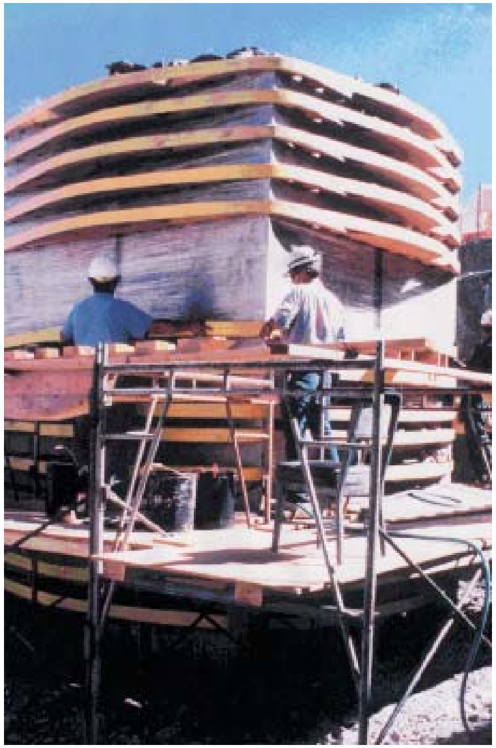
We can also apply the same methods for imaging core and blocks (and any shape object)





The methods may be used to look at changes within the block or core due to changing environmental conditions or hydraulic loading



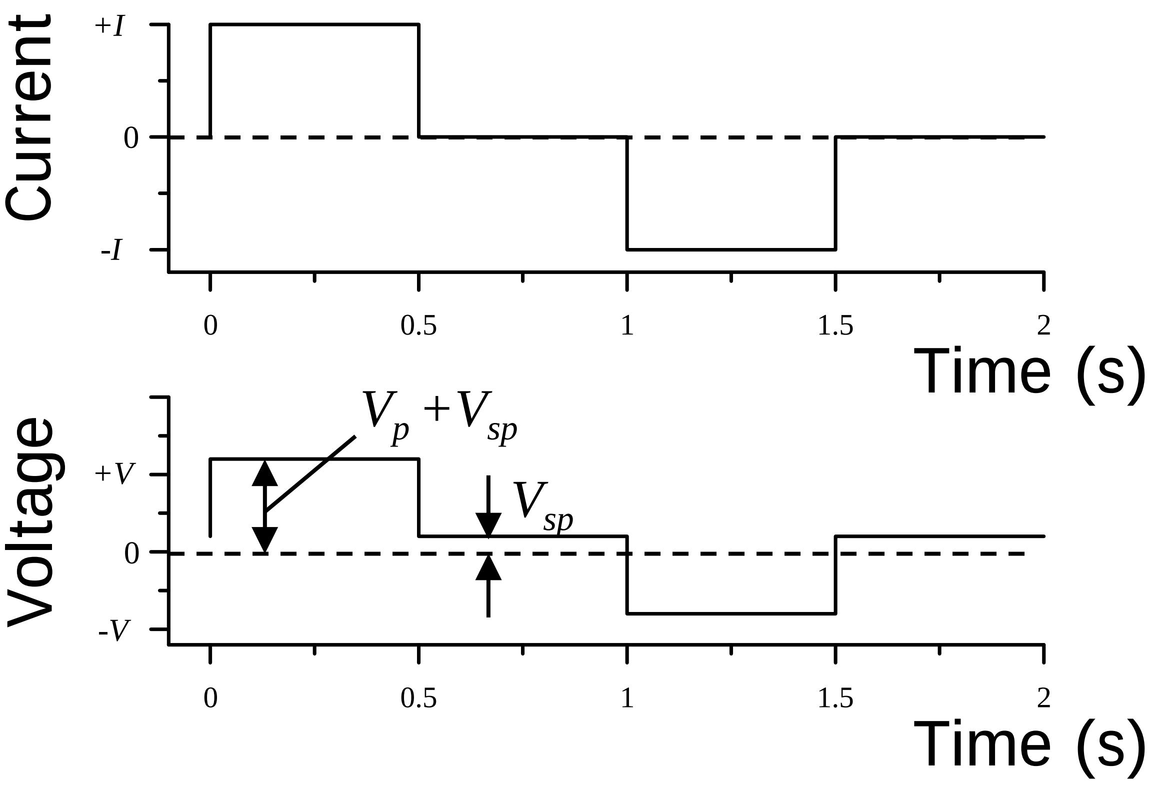


After Ramirez & Daily (2000)

IP measurement principles

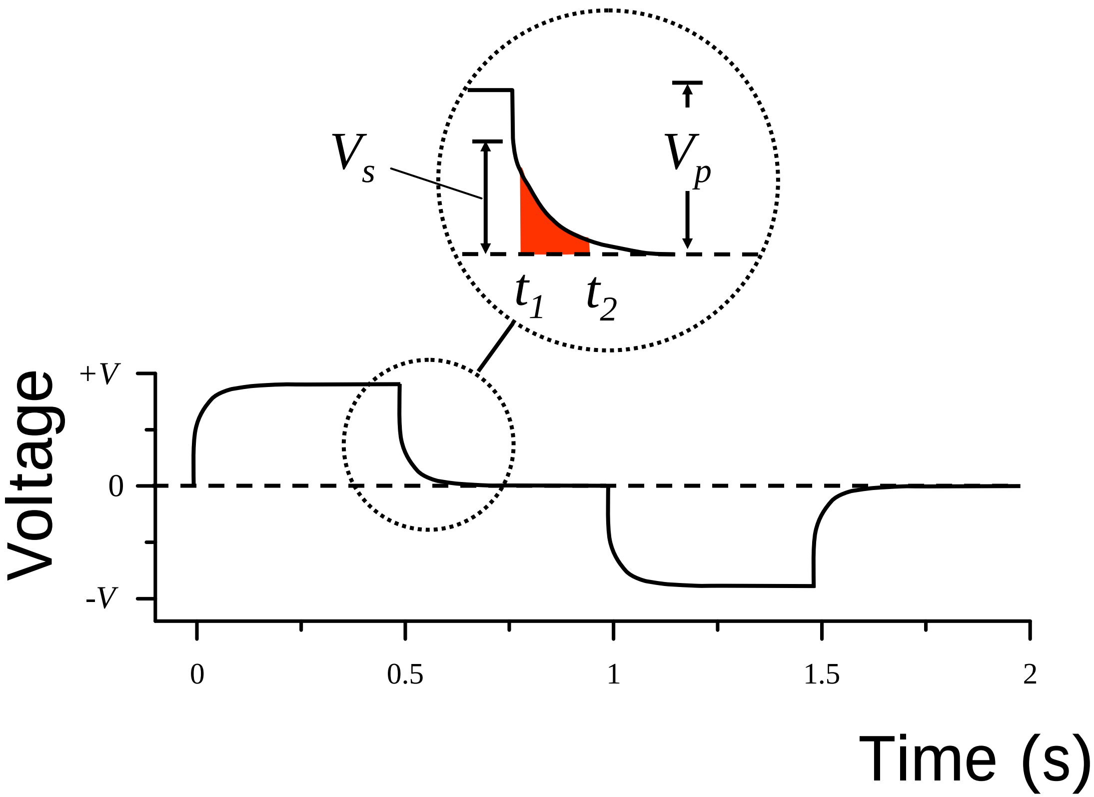
So far we have just looked at DC resistivity

Recall the expected response of the voltage measurement:



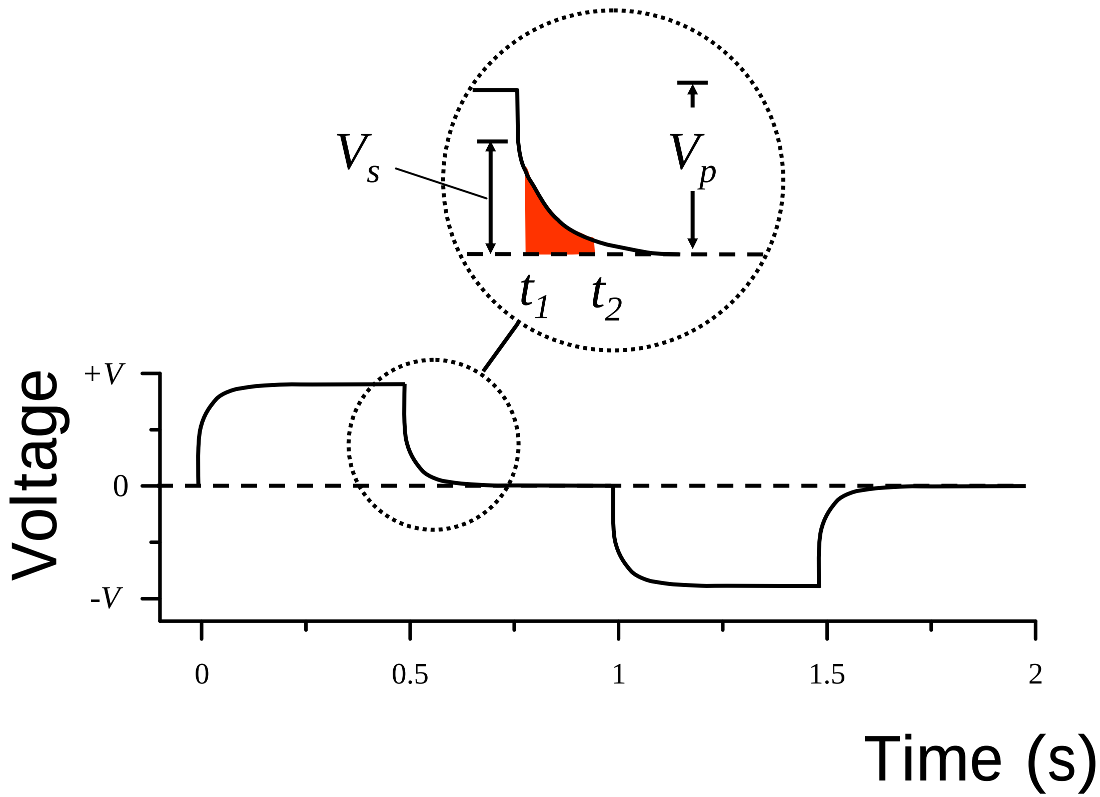
In practice, there is a charge up and charge down response.

This forms the basis of time domain induced polarisation measurements



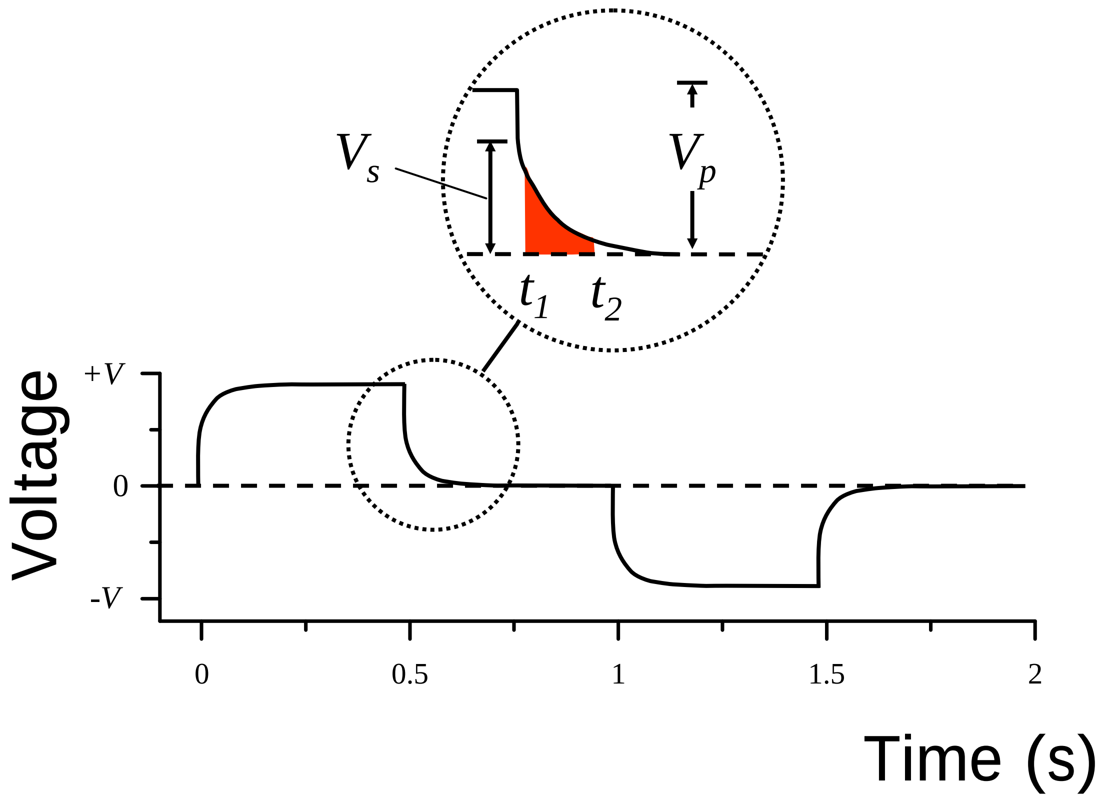
Seigel (1959) defined the *apparent chargeability* as: $m_a = \frac{V_s}{V_p}$

V_p is the primary voltage and V_s is the secondary voltage



But V_s is difficult to measure accurately and so an integral measure of chargeability is normally used:

$$m_a = \frac{1}{(t_2 - t_1)} \frac{1}{V_p} \int_{t_1}^{t_2} V(t)dt \quad \text{(units mV/V)}$$



But V_s is difficult to measure accurately and so an integral measure of chargeability is normally used:

$$m_a = \frac{1}{(t_2 - t_1)} \frac{1}{V_p} \int_{t_1}^{t_2} V(t)\,dt \quad \text{(units mV/V)}$$

Note that the measurement is dependent on the chosen time window (and so is never an intrinsic measure).

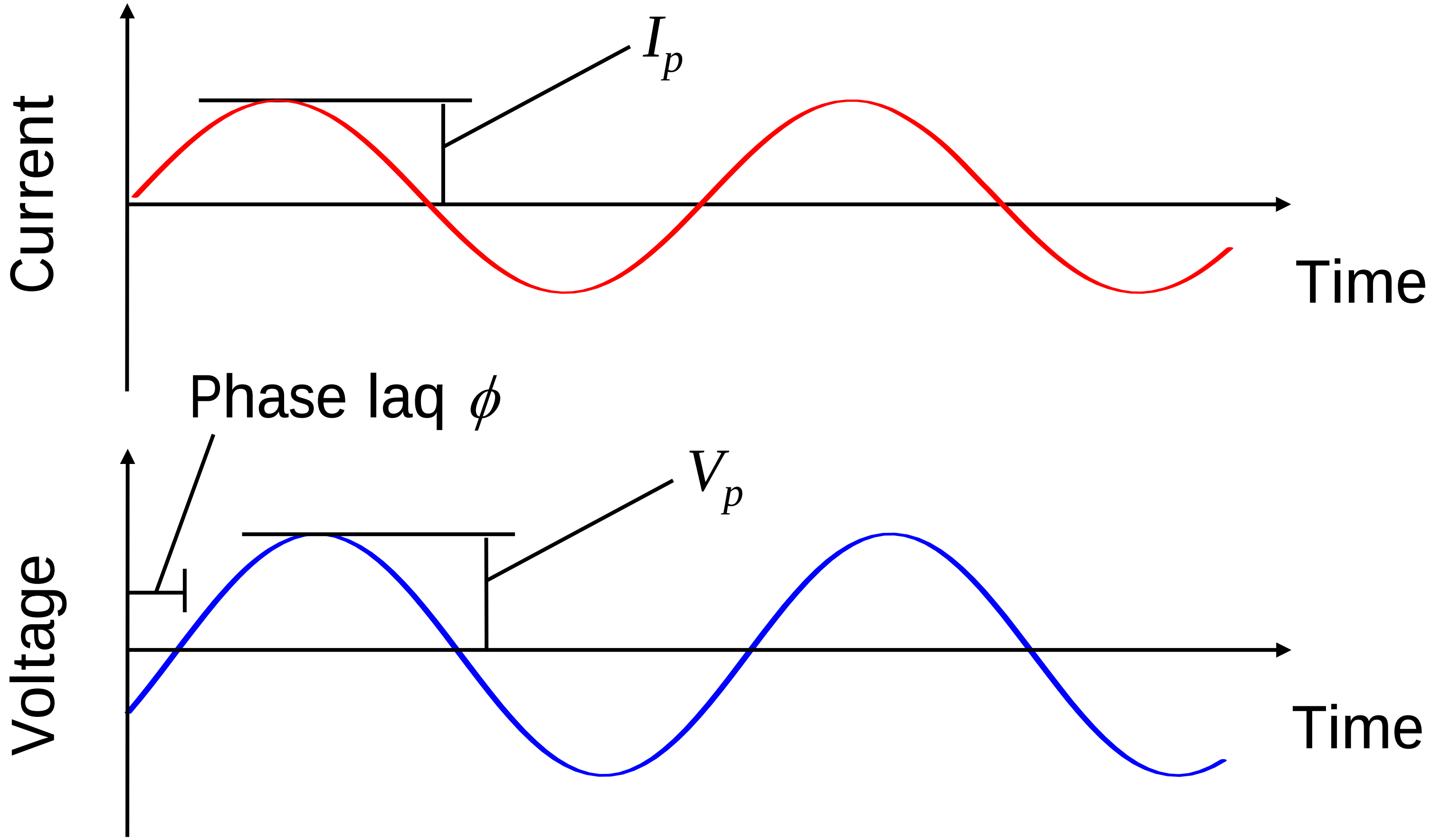
Also note that the charge up and charge down effect (if strong) can influence the DC resistivity readings.

To measure IP non-polarising potential electrodes (e.g. copper-copper sulfate in a porous pot) are normally used.

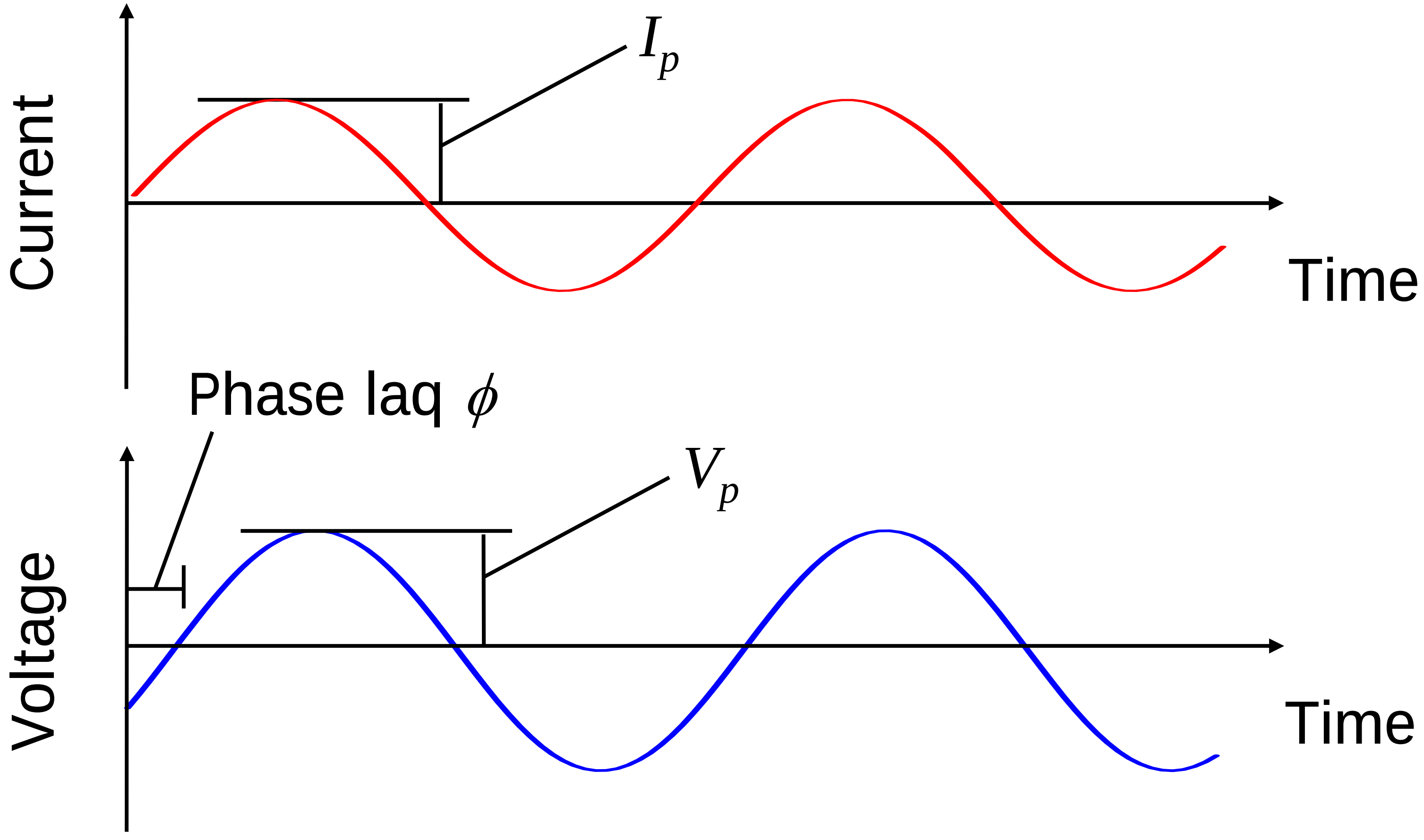
Injection currents need to be much higher than normal DC resistivity measurements to ensure good voltage signals.

Also electrical coupling across cables can be a problem and so multi-core cables used for DC resistivity may be problematic.

IP can also be measured in the *frequency domain* by looking at the change in amplitude and phase lag of an injected and measured signal.



The measurement is thus a complex resistivity with magnitude $|\rho| = V_p/I_p$ and phase ϕ



The advantage of the complex resistivity measurement is that it is an intrinsic measure.

Frequency domain instruments are typically more expensive than time domain IP instruments. Few multi-electrode systems are available.

(a)

(b)

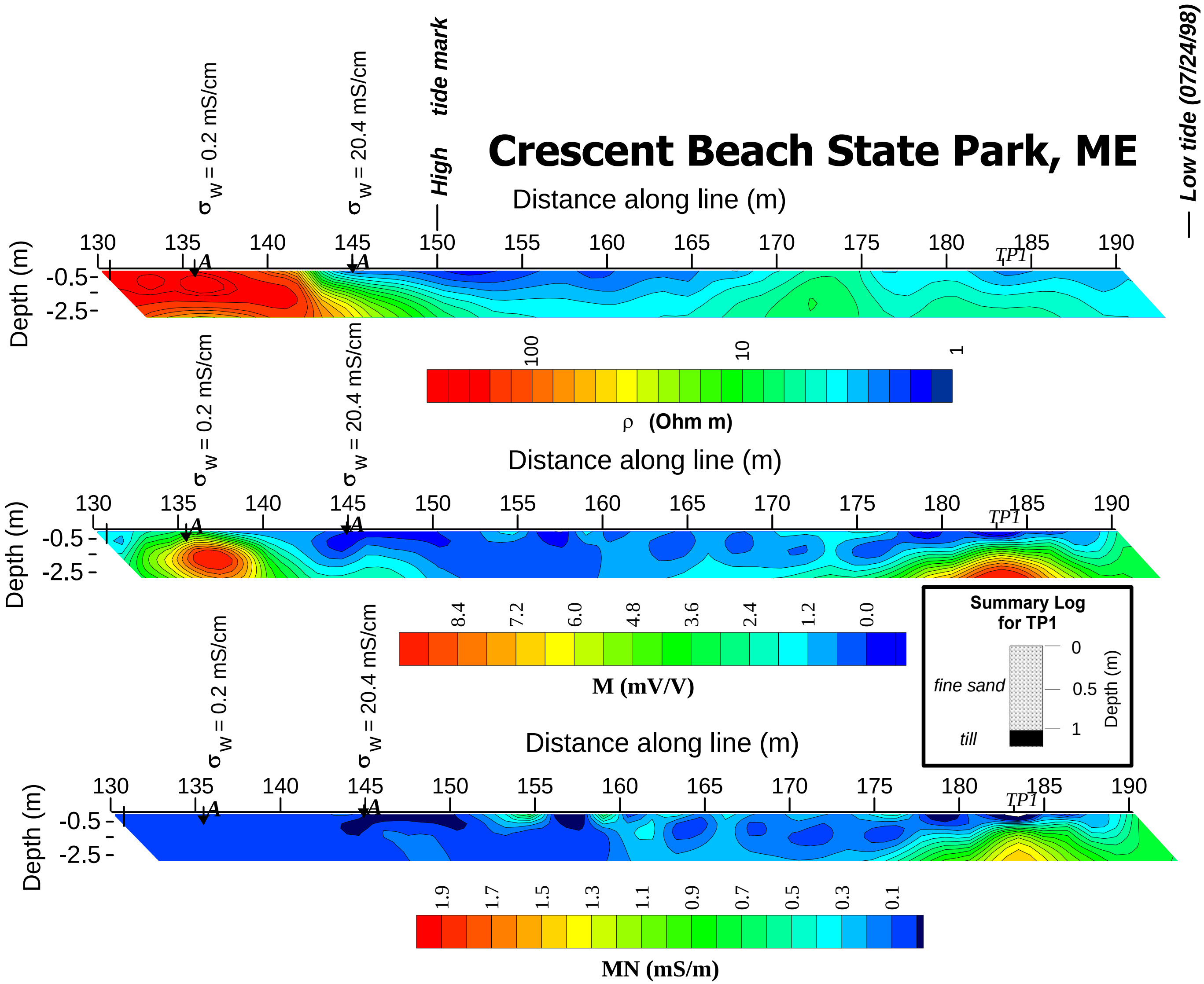
(a) SIP Fuchs II base unit and fiber optic cable reels
(b) Zonge GDP32 receiver

Separating lithological variation from fluid chemistry changes:

Resistivity

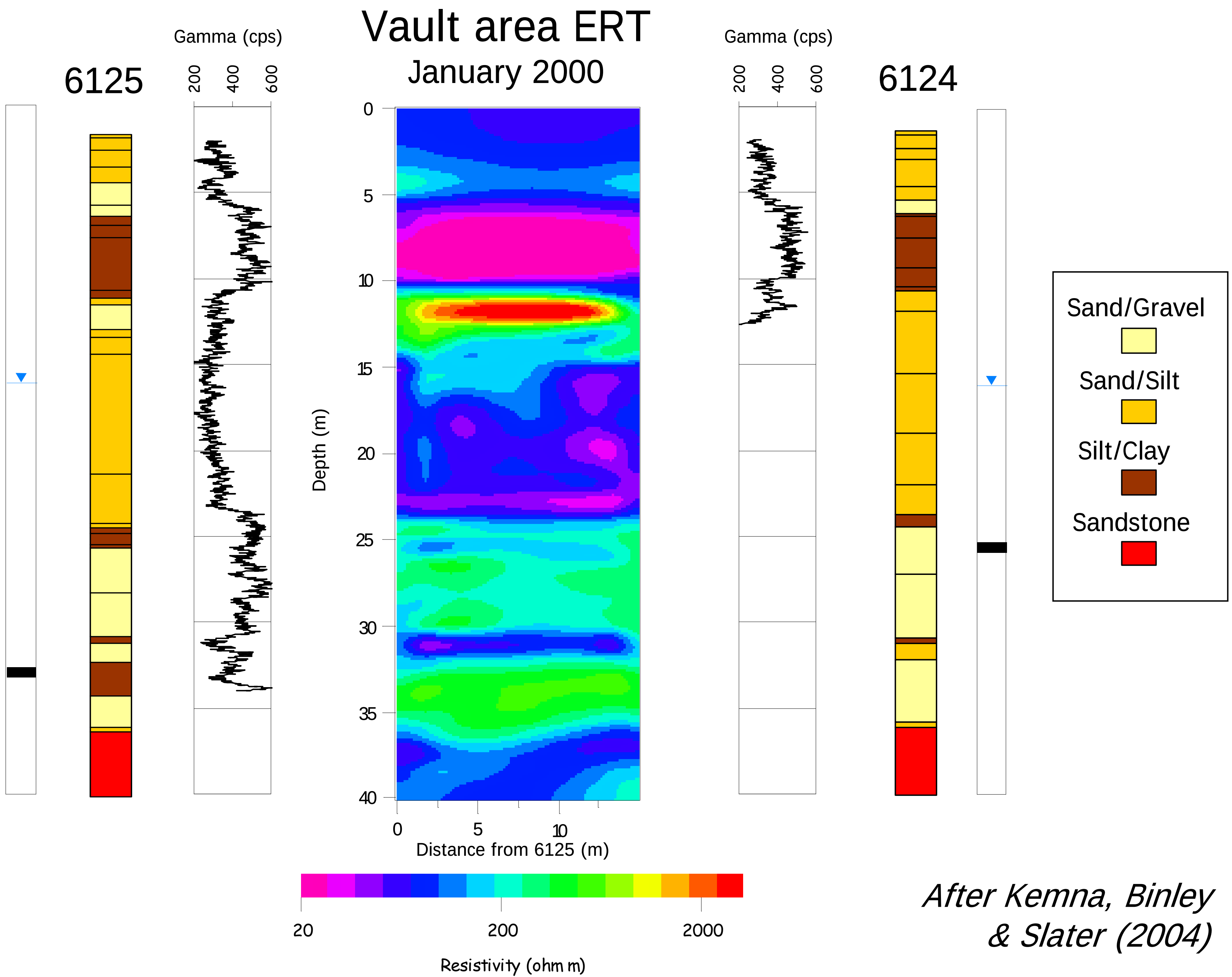
Relative measure of IP:

Direct measure of IP: **not influenced by fluid chemistry**



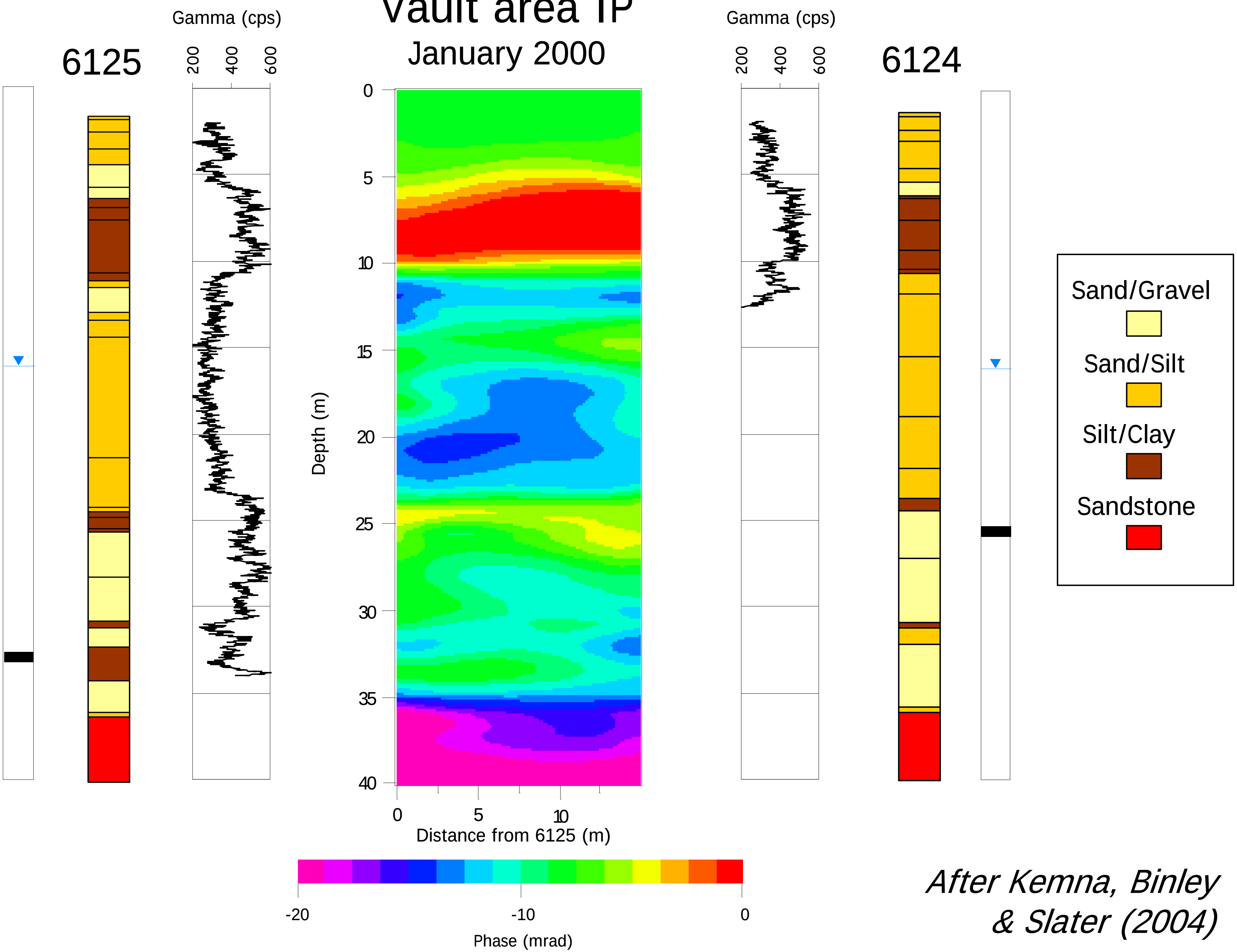
After Slater & Lesmes (2001)

Cross-borehole ERT and IP imaging at the Drigg nuclear waste disposal site


Vault area ERT
January 2000
6125
Gamma (cps)
200
400
600
Gamma (cps)
200
400
600
6124
0
5
10
15
20
25
30
35
40
Depth (m)
0
5
10
Distance from 6125 (m)
Sand/Gravel
Sand/Silt
Silt/Clay
Sandstone
20
200
2000
Resistivity (ohm m)
After Kemna, Binley & Slater (2004)

Vault area IP

January 2000



After Kemna, Binley & Slater (2004)

Summary

DC resistivity and IP can be measured in varied geometrical arrangements.

Pseudosections have limited value as an *image* of the subsurface but are useful (for surface imaging) as a data check.

The choice of measurement scheme can have an effect on the final image.

IP will be sensitive to electrode material and other factors. Care must be taken in obtaining IP measurements.

Inverse methods can be used to determine images of resistivity and IP (next lecture).