Electromagnetic methods
Main concepts

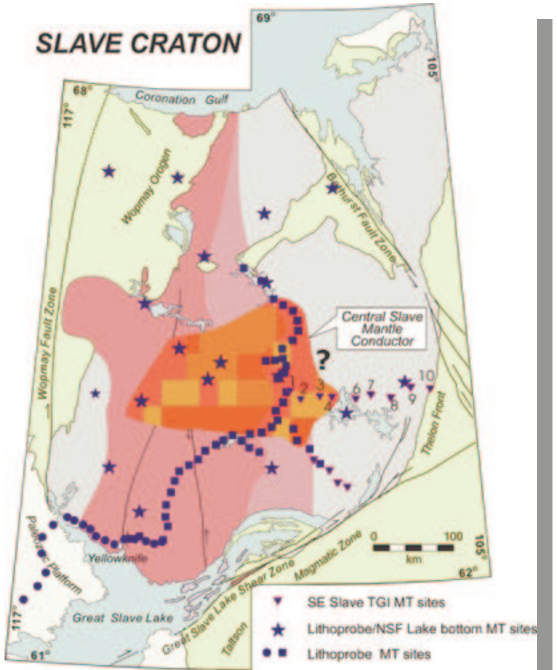
- Resistivity surveying
  ... Aims at investigating variations in electrical resistance (inverse of conductivity), causing an electric current through the ground
- Electromagnetic (EM) surveying
  ... no use of wires, thus possible use in aerial surveys
- Ground-penetating radar (GPR)
  ... Records radar waves reflected from interfaces allowing a direct image of the subsurface, limited to top few meters
- Magnetotelluric (MT) surveying
  use of natural currents in the ground, combining EM and resisitivity techniques, depth range to several hundreds of km
- Self-potential (SP)
  prospecting of ores using natural production of electricity
- Induced polarization (IP)
  uses electricity storage capacity of ores, and its release after turning off an external field

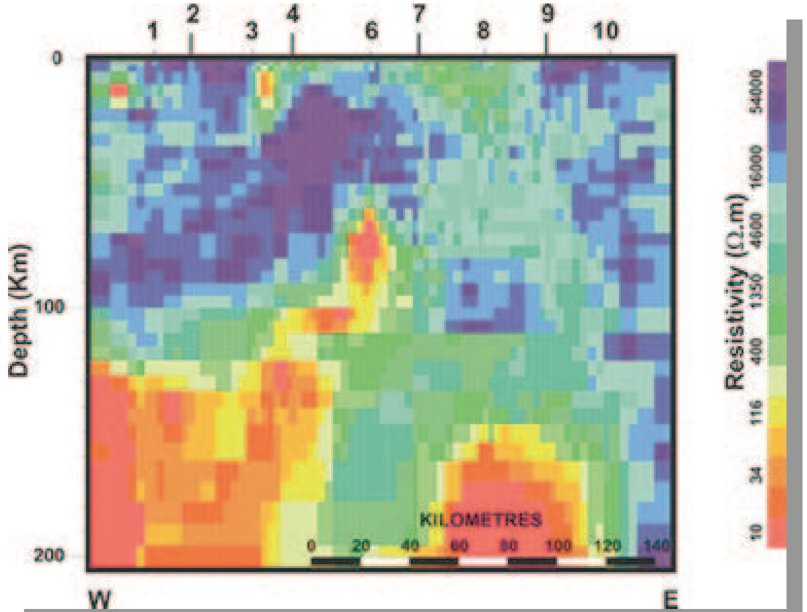
This lecture follows ***Musset and Khan, Looking into the Earth***

Electromagnetic methods
Domains of application

- Mineral prospecting
- Hydrogeological surveys
- Ground contamination surveys
- Site investigations
- Archeological surveying

MT example
(pictures from Alan Jones)

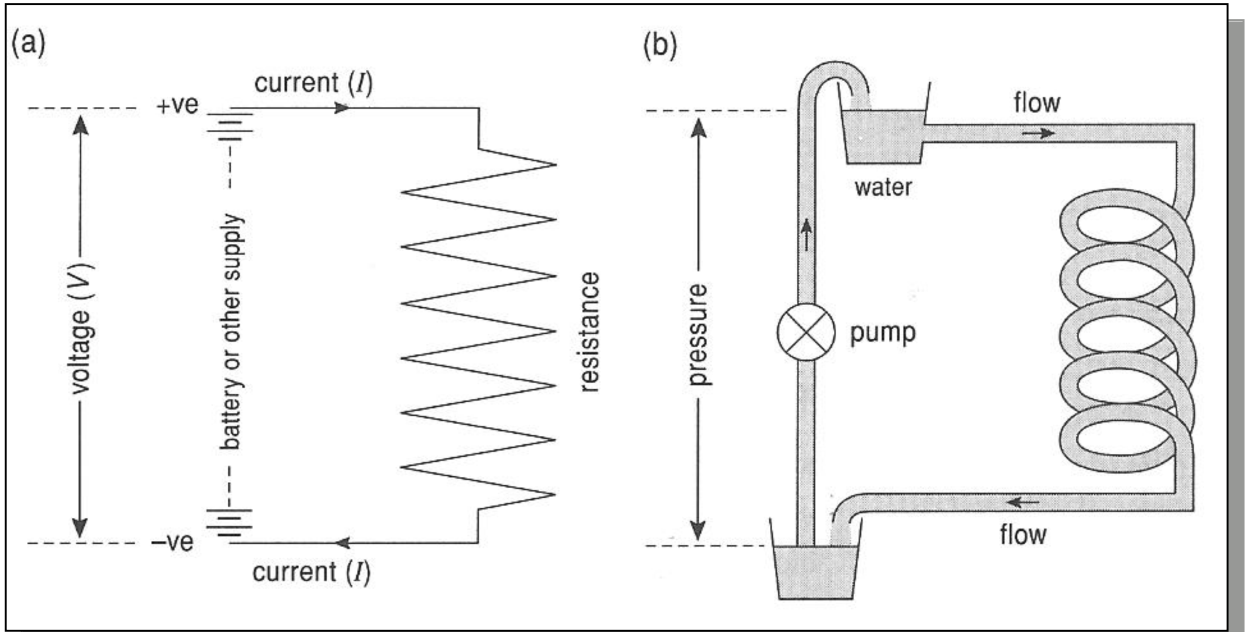




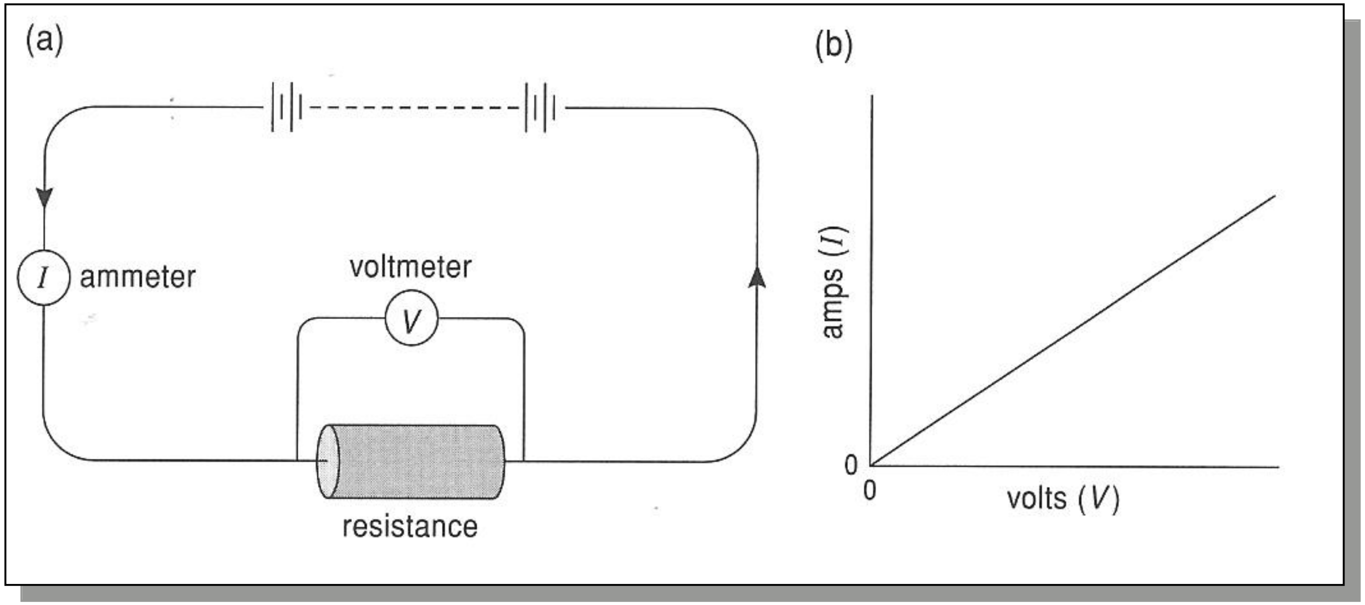
Resistivity methods

Resisitivity (inverse of conductivity) of rocks depend on the amount of **groundwater** present, amount of **dissolved salt**, and the presence of **ore minerals** and **temperature**

We will develop the techniques to investigate the vertical structure of a layered Earth model, **v**ertical **e**lectrical **s**ounding (**VES**)



Ohm's Law



Current I is proportional to voltage V with proportionality constant resistance R

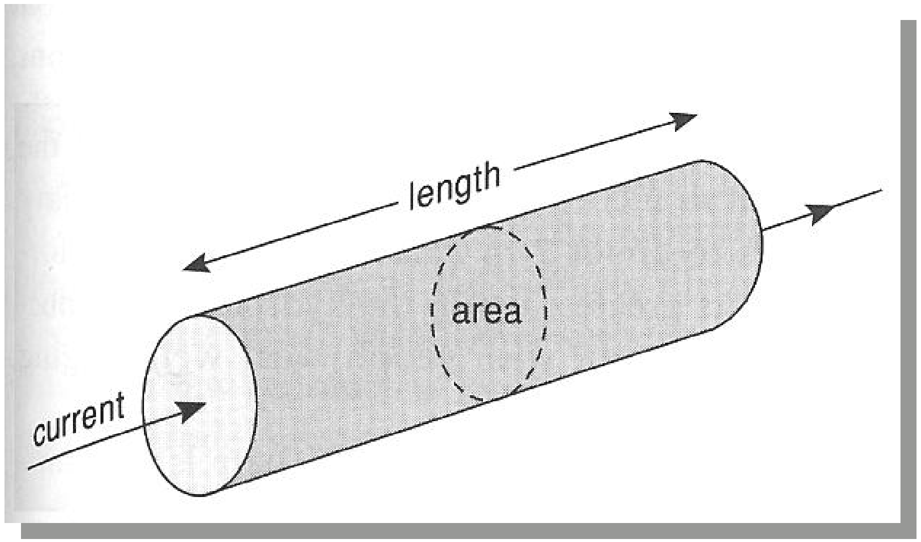
$$V = R I$$

The current at V=1 Volt is called the resistance

Effects of material and shape

The amount of current flowing through an object depends on the materal and its shape, this is quantified for a rod of length l and area A

This leads to the distinction between **resistance** and **resistivity**



Resistance R = resistivity (ρ) x (length/area of cross section)

resistivity (ρ) = Resistance R x (area of cross section/length)

We are of course primarily interested in estimating **resistivity**

Conductors – Insulators

low resistivity – high resistivity

high conductivity – low conductivity

Good insulators: quartz

Good conductors: salt water, silver, graphite

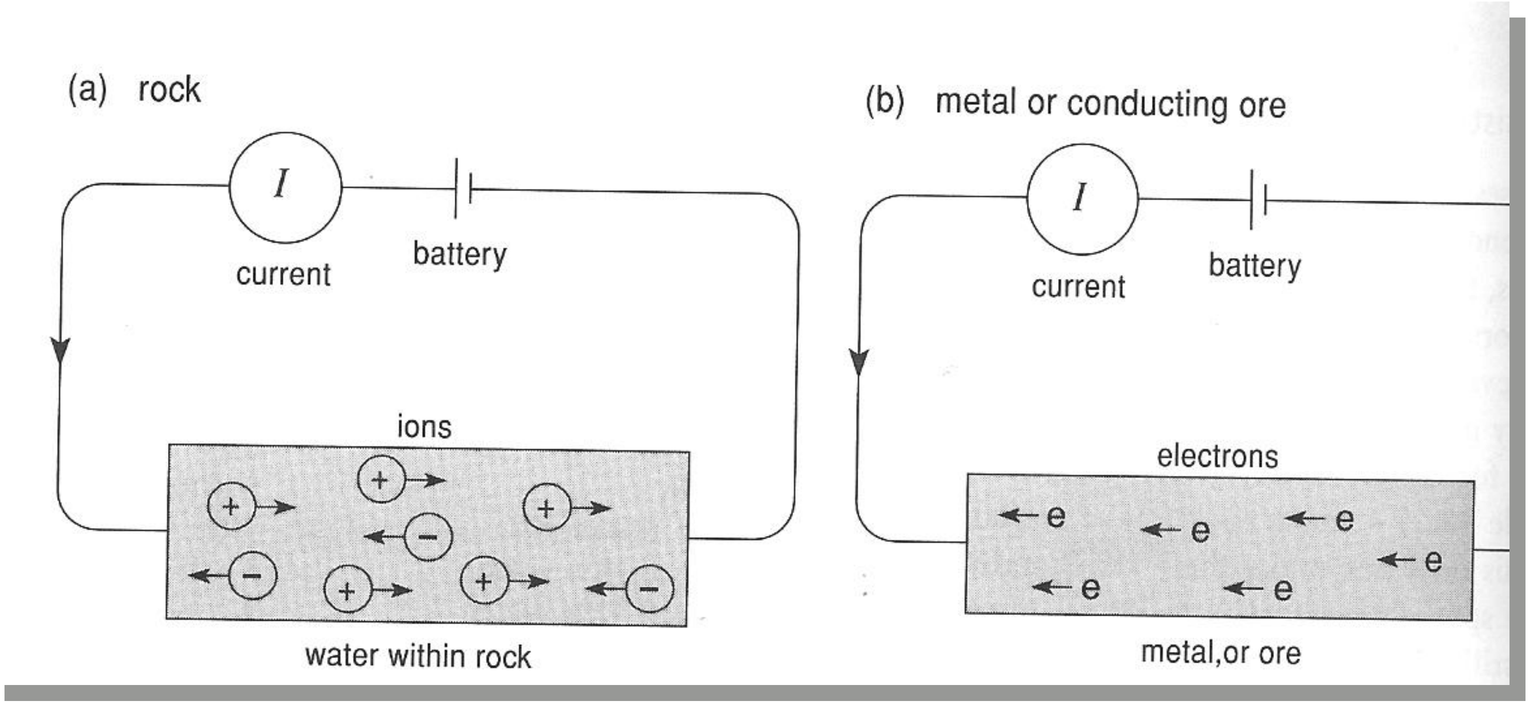
Note the wide range of resistivity over almost 20 orders of magnitudes

Resistivity of rock depends mainly on porosity, water saturation, and the water conductivity (salt content)

Rocks, minerals, ores	Resistivity (ohm-m)
Sediments	
chalk	50–150*
clay	1–100
gravel	100–5000
limestone	$50–10^7$
marl	1–100
quartzite	$10–10^8$
shale	10–1000
sand	500–5000
sandstone	$1–10^8$
Igneous and metamorphic rocks	
basalt	$10–10^7$
gabbro	$1000–10^6$
granite	$100–10^6$
marble	$100–10^8$
schist	$10–10^4$
slate	$100–10^7$
Minerals and ores	
silver	1.6×10^{-8}
graphite, massive ore	$10^{-4}–10^{-3}$
galena (PbS)	$10^{-3}–10^2$
magnetite ore	$1–10^5$
sphalerite (ZnS)	$10^3–10^6$
pyrite	1×100
chalcopyrite	$1 \times 10^{-5}– 0.3$
quartz	$10^{10}–2 \times 10^{14}$
rock salt	$10–10^{13}$
Waters and effect of water and salt content	
pure water	1×10^6
natural waters	$1–10^3$
sea water	0.2
20% salt	5×10^{-2}
granite, 0% water	10^{10}
granite, 0.19% water	1×10^6
granite, 0.31% water	4×10^3

*Values or ranges, which have come from several sources, are only approximate.

Ionic and electronic conduction



Dissolution of salts leads to the presence of ions that increase conductivity (e.g., Na^{+}, Cl^{-}) -> ionic conduction. Electronic conduction is the flow of free electrons in metals.

Porous media – Archie's Law

The **formation resistivity** (i.e., resistivity of a porous rock) can be calculated knowing the porosity ϕ, the saturation S (fraction of pore space filled with water)

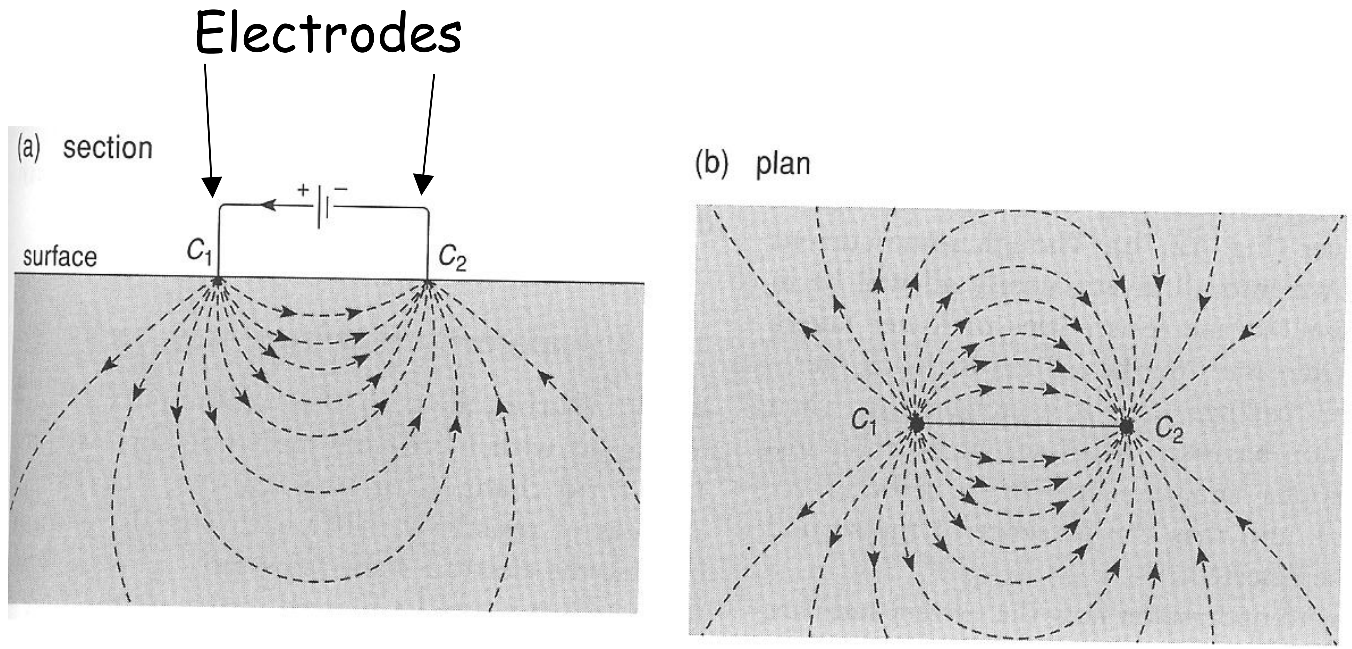
Archie's Law

$$\rho_t = a \frac{\rho_w}{\Phi^m S_w^n}$$

R_w is the resistivity of water, m,n, and a are constants that are determined from lab or field experiments, a is in the range of 0.5-2.5, n is about 2, m depends on the age of rocks. Archie's law is widely used in the hydrocarbon industry particularly in connection with well logging.

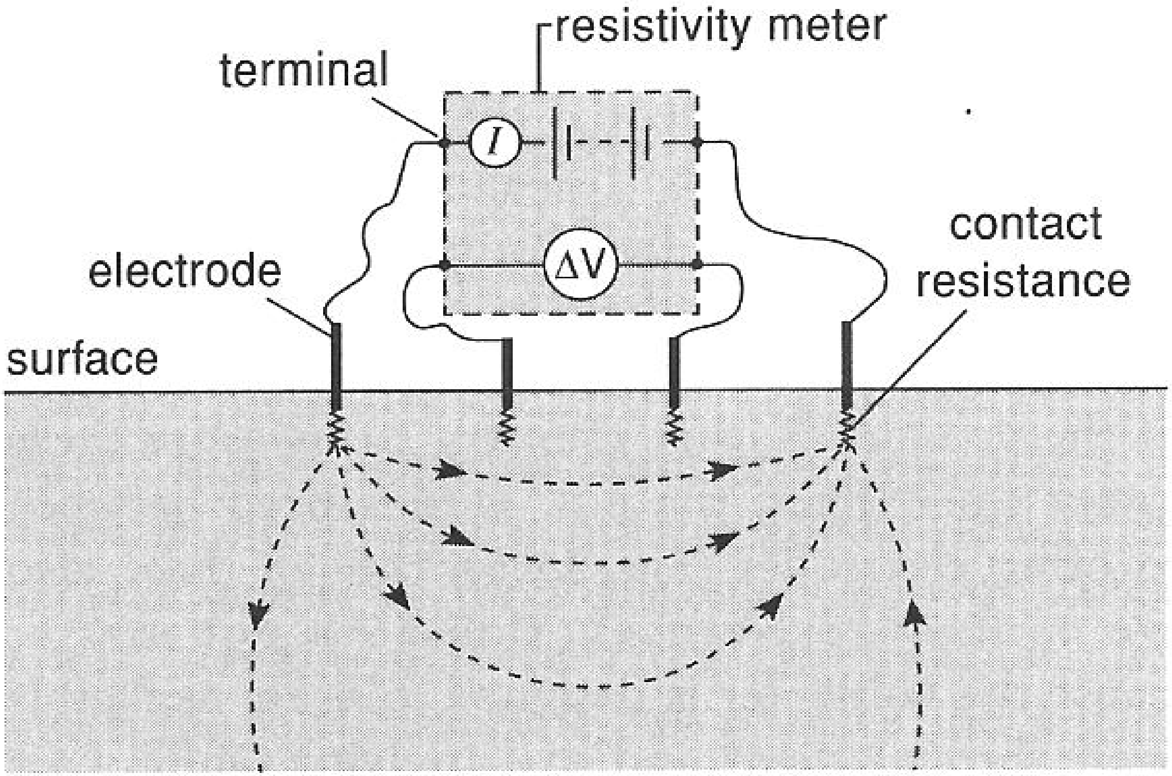
Electricity Flows

In uniform media only 30% of the current flows deeper than the separation distance of the electrodes.



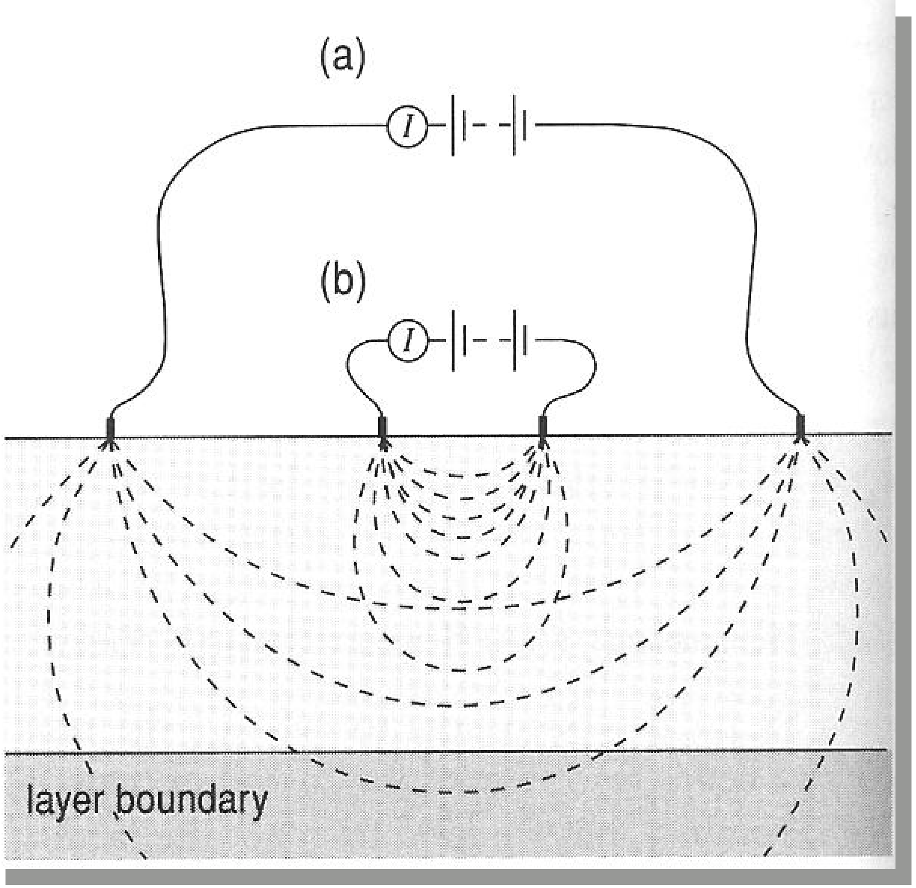
Resistivity meter

The actual resistivity is measured by two additional electrodes to those injecting the current.



Vertical electrical sounding

Principle: Expand the electrode array from a fixed centre.



Refraction

Refraction changes the distribution of current in the ground as the ratio of ΔV/I is also changed ... this effect is used to estimate the changes in resistivity ...

$$\rho_1 \tan\theta_1 = \rho_2 \tan\theta_2$$

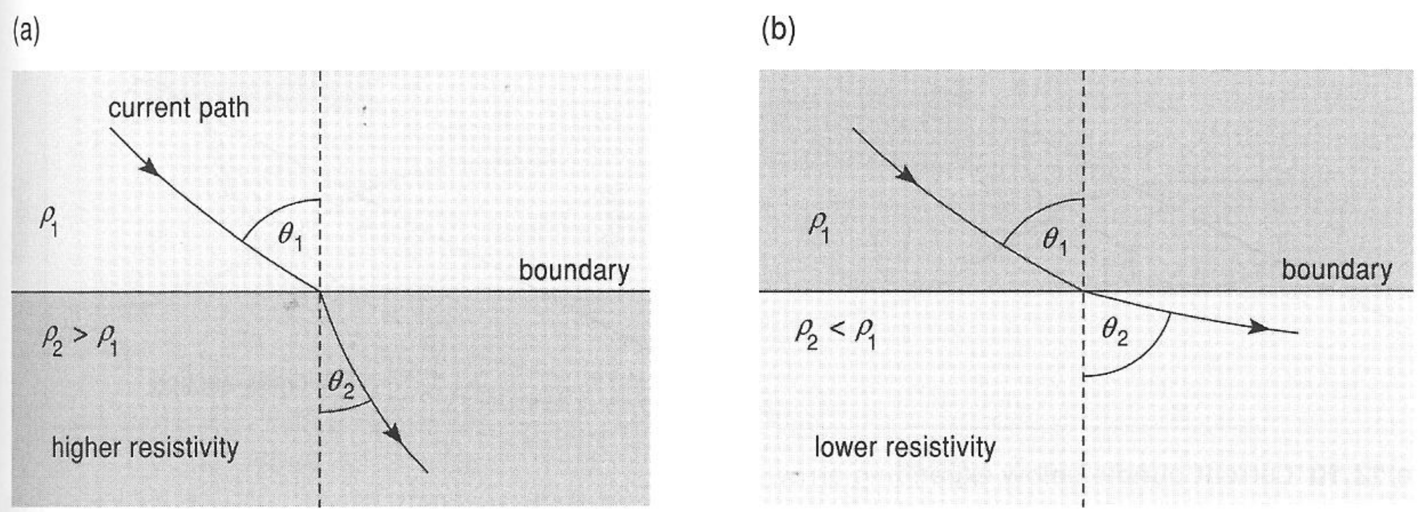
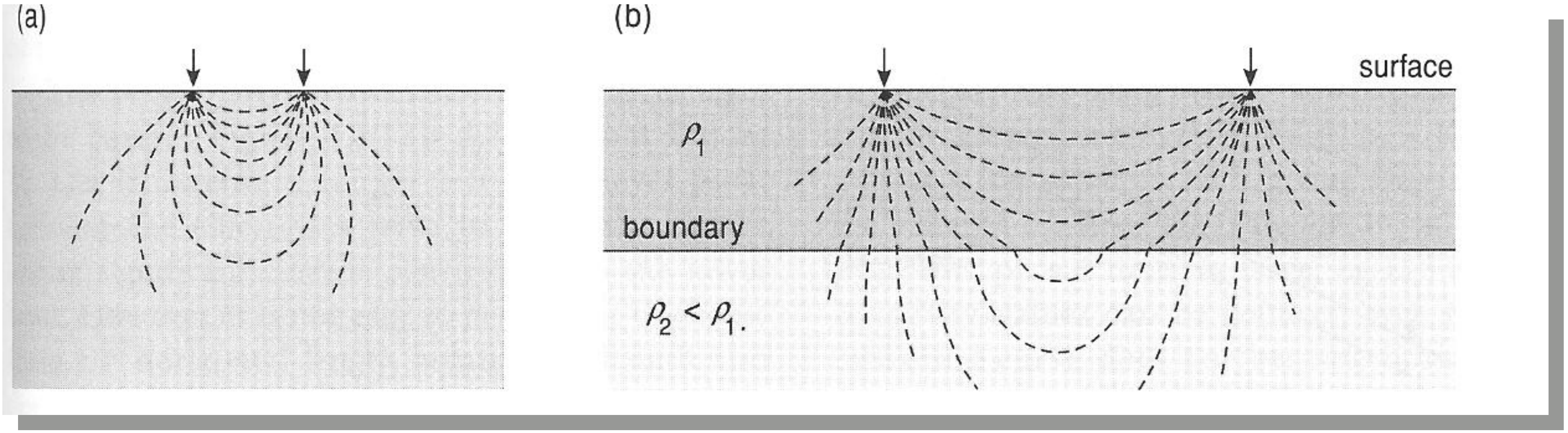


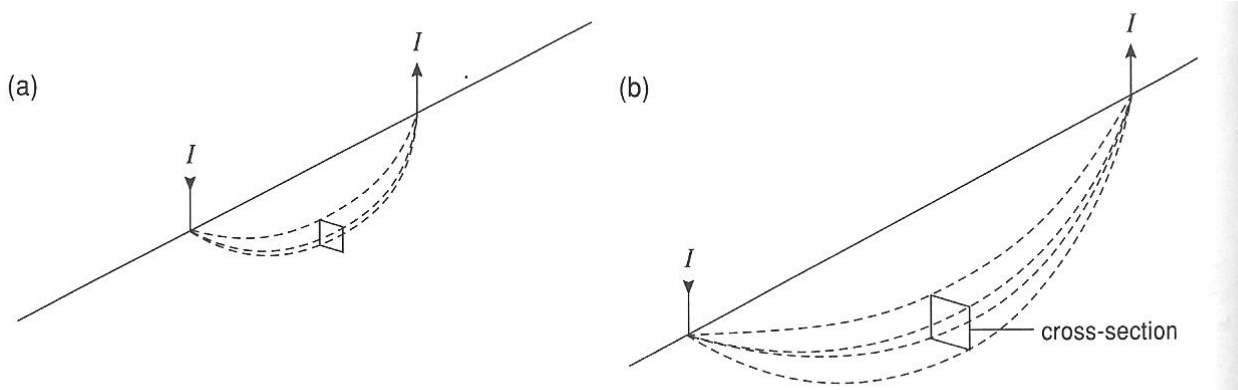
Figure 12.8 Refraction of current flow lines.

Refraction – Flow lines



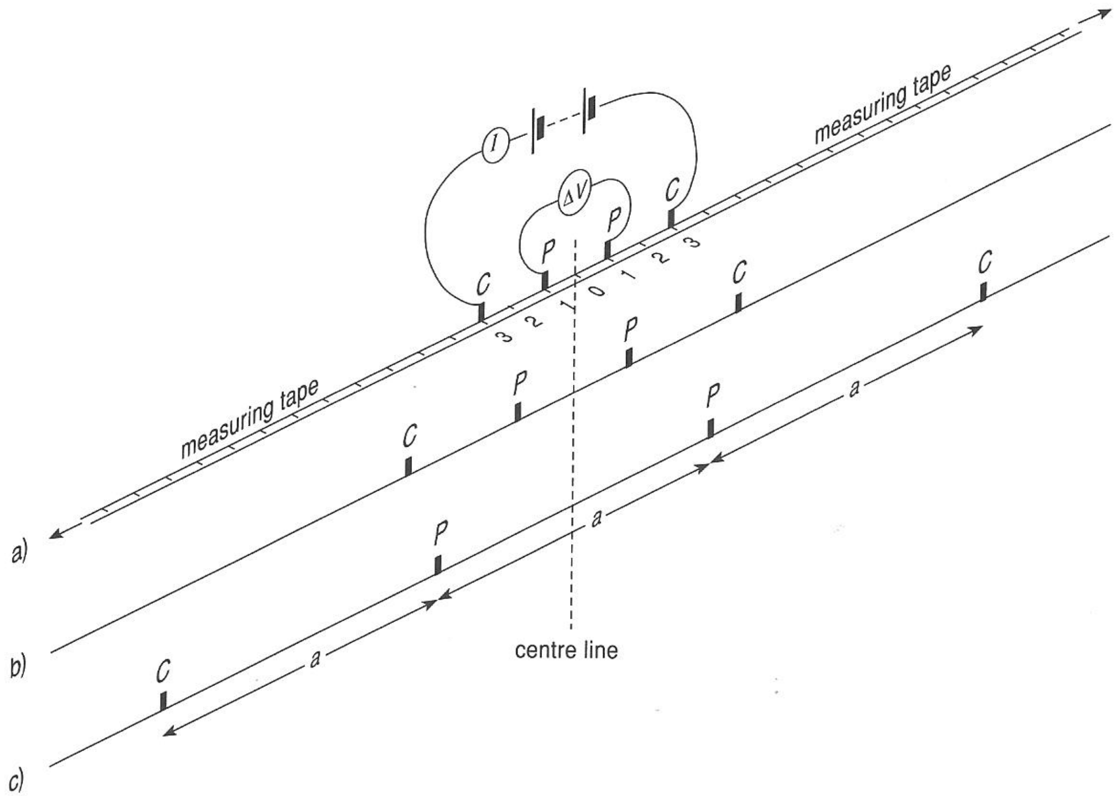
Apparent resistivity

Increasing the distance alone changes the resistance, as the length increases but the cross section area also ... -> increasing the distance lowers the resistance in a uniform medium ... To correct for this the observed resistance has to be corrected for by a geometrical factor



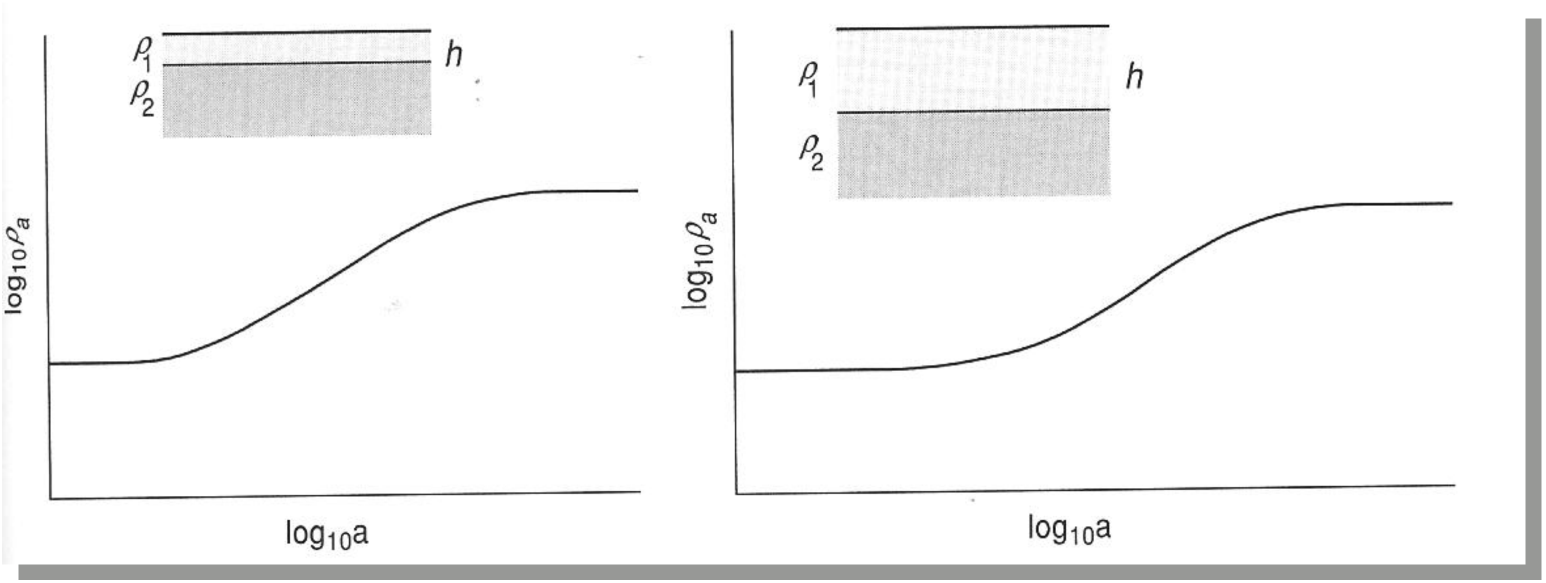
The geometrical factor is chosen such that for a uniform subsurface the resistance does not change with electrode distance and is equal to the ground's resistivity

The Wenner Array



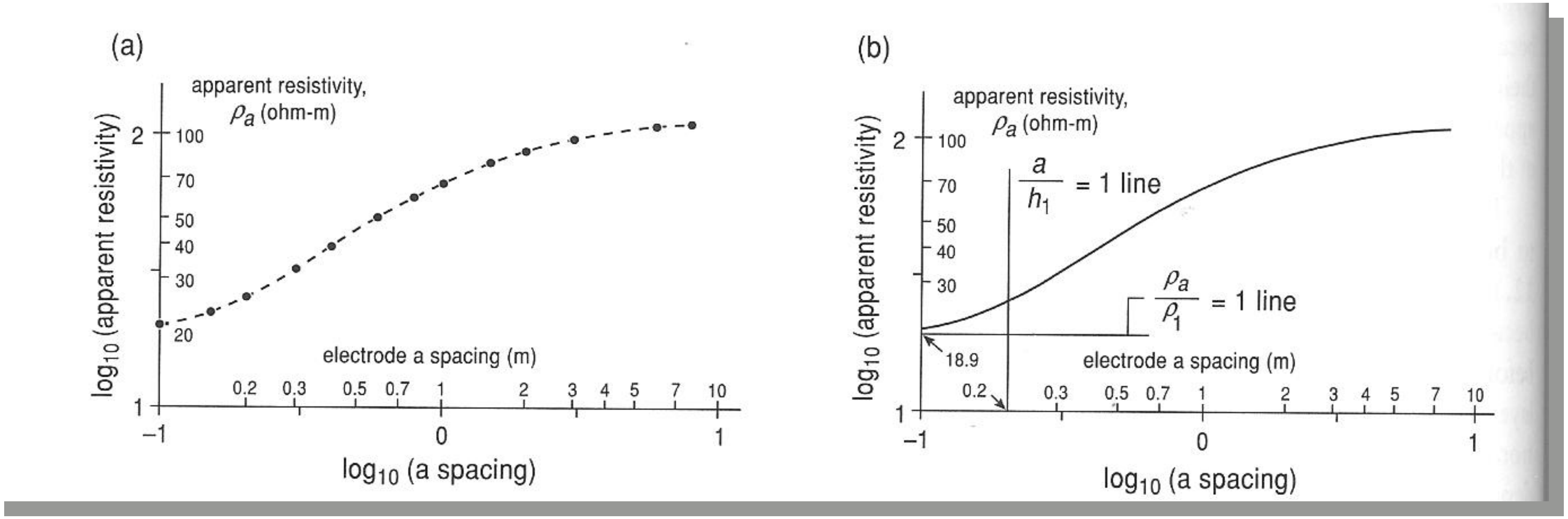
The geometrical factor for the Wenner Array is $2\pi a$, a being the electrode distance

Typical observation, after correction

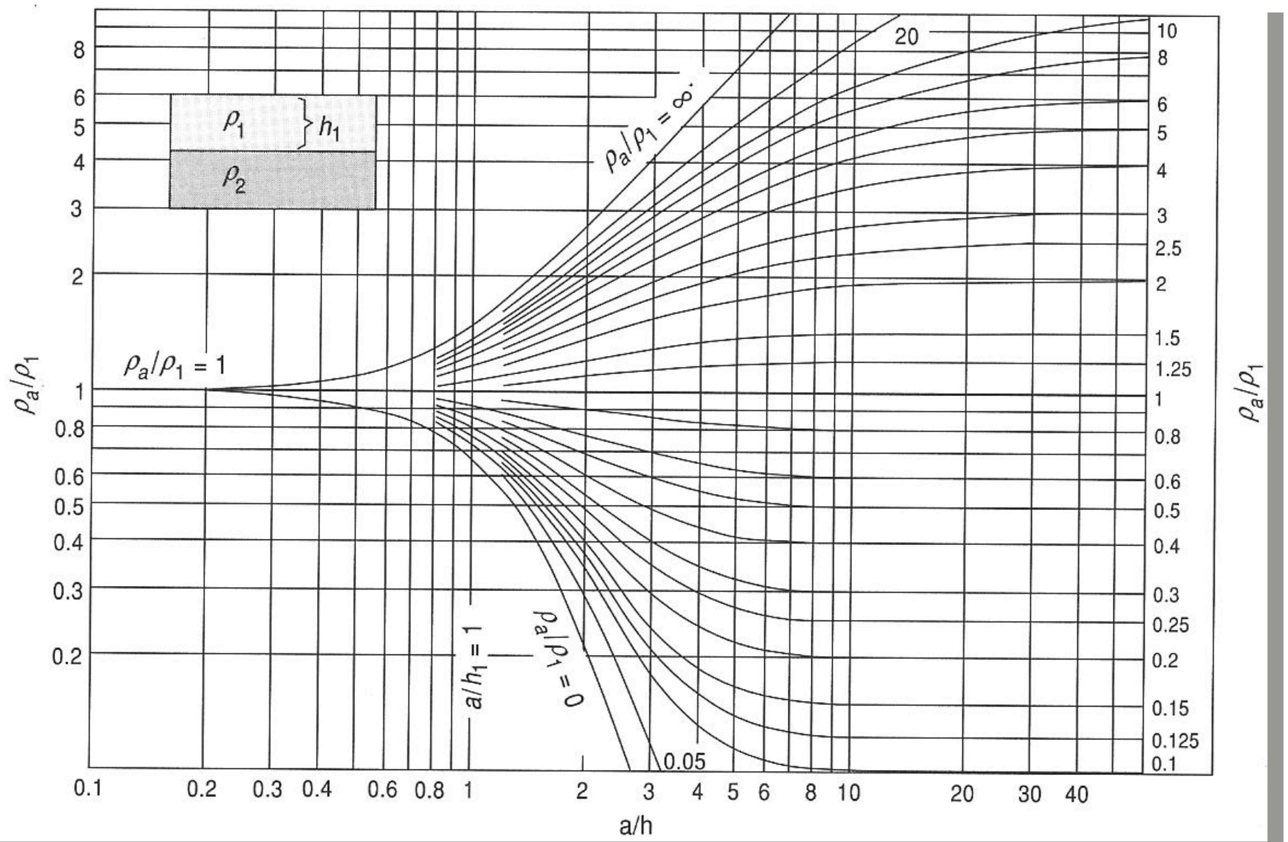


Increase of resistivity with electrode distance – lower material has higher resistivity

Observation

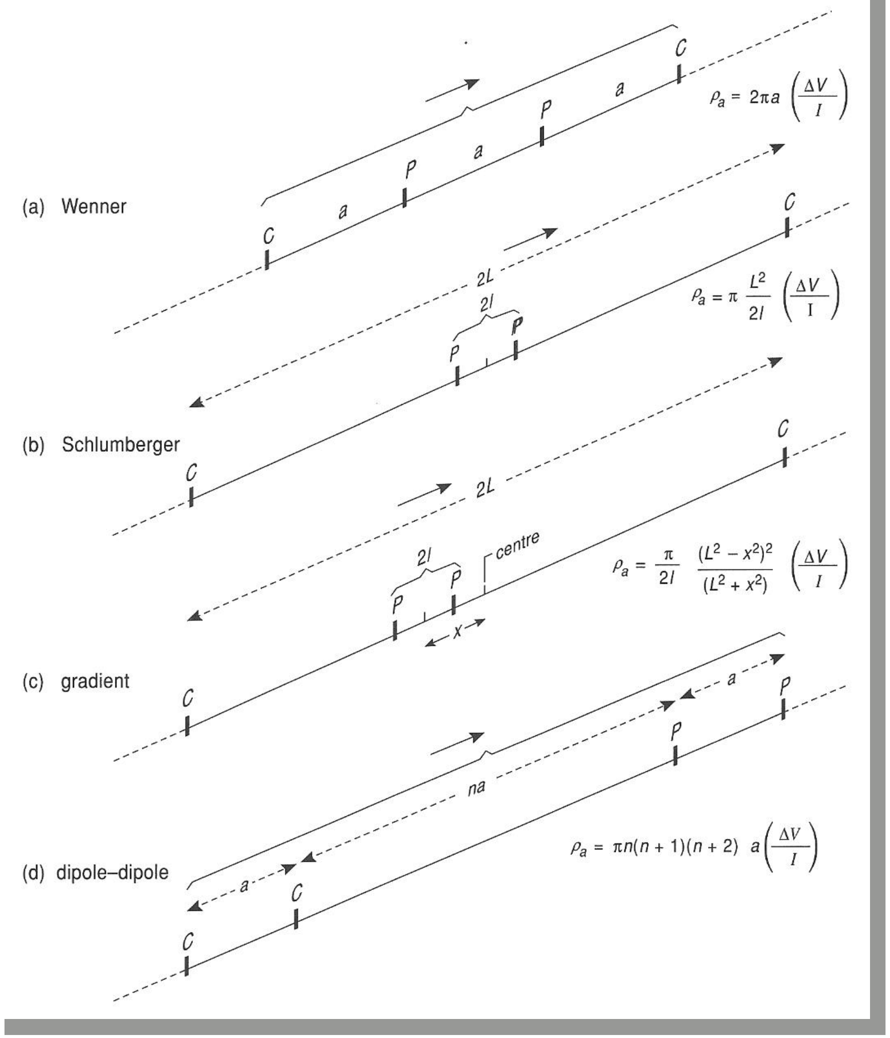


Master curves



In the two layer case the thickness of the top layer can be found by comparison with this Master curve

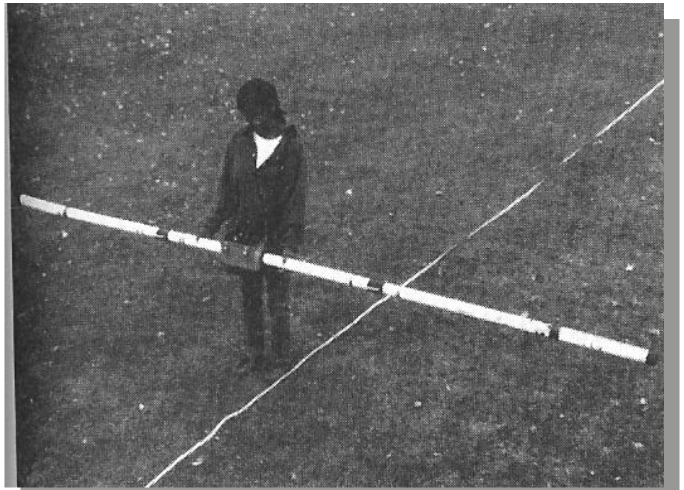
Other arrays



Some general remarks

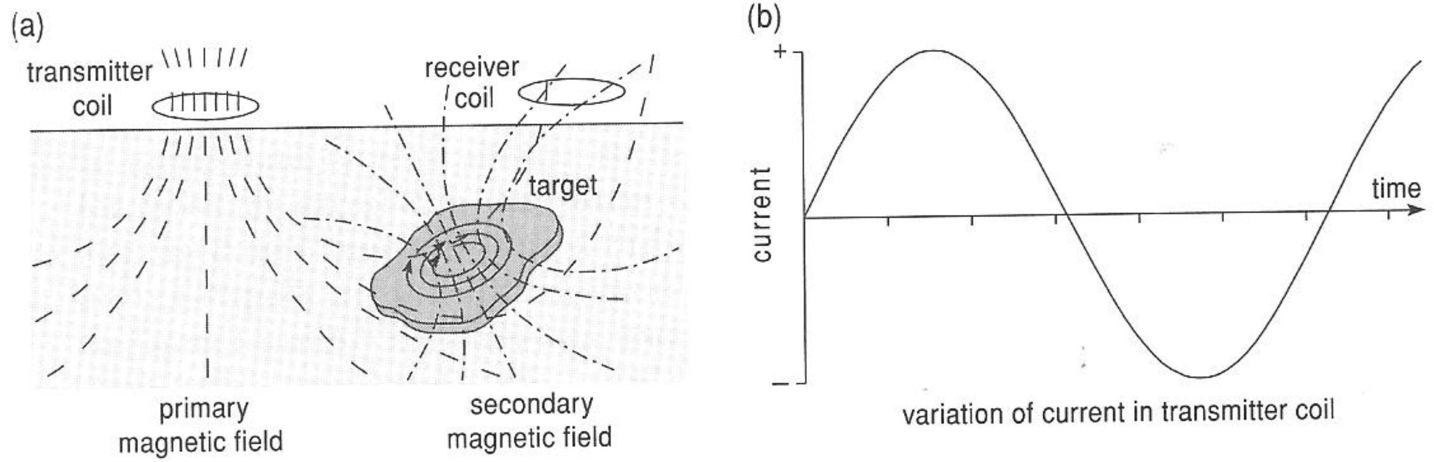
- Maximum detectable depth: depends on the electrode separation and the resistivity model. Rule of thumb: depth range 50% of the electrode separation
- Penetration may be limited by too low voltage -> increase current or average several readings
- Resolution: Depends on thickness **and** depth. The shallower the layer the better the resolution
- The world is of course not layered, expected model geometries and structures should be tested before to see whether they would be detectable
- Layers may be anisotropic, i.e. measurements should be carried out at least in two (e.g., orthogonal) directions

Electromagnetic surveys



- Similar to resistivity surveys but e-m methods induce current flows without using electrodes (-> possible use in aerial surveys)
- Useful when surface layer has high resistivity
- Conductive surface layers limit e-m methods
- Less precise than resistivity modelling
- Quick useage compared to resistivity methods

Electromagnetic induction

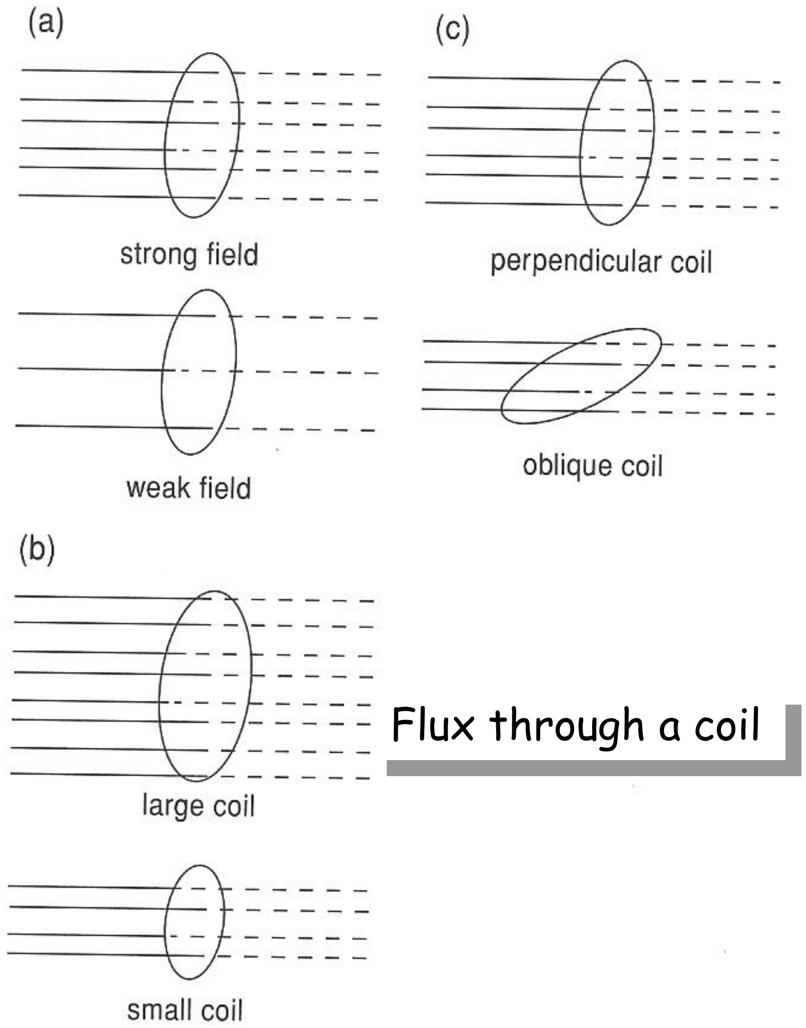


- An alternating current is flowing through the transmitter coil
- The resulting time-varying magnetic field induces currents, and thus a secondary magnetic field, that is observed by the receiver coil

The e-m signal

How does the current in the receiver coil depend on its geometry? It is affectedy by
- The number of magnetic field lines through the loop
- The rate of change of this number
- Material of the loop

The magnetic flux depends on
- Strength of magnetic field
- Area of the loop
- Angle of loop with field lines



Flux through a coil

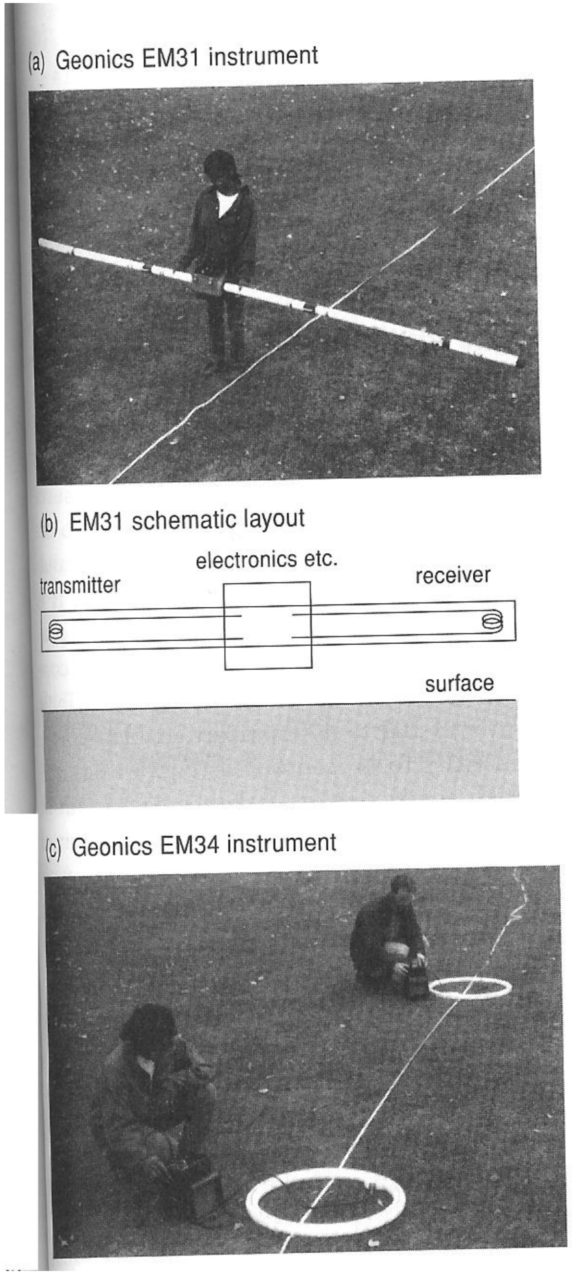
E-M systems

Frequency of alternation range from hundreds to tens of thousands of Hertz

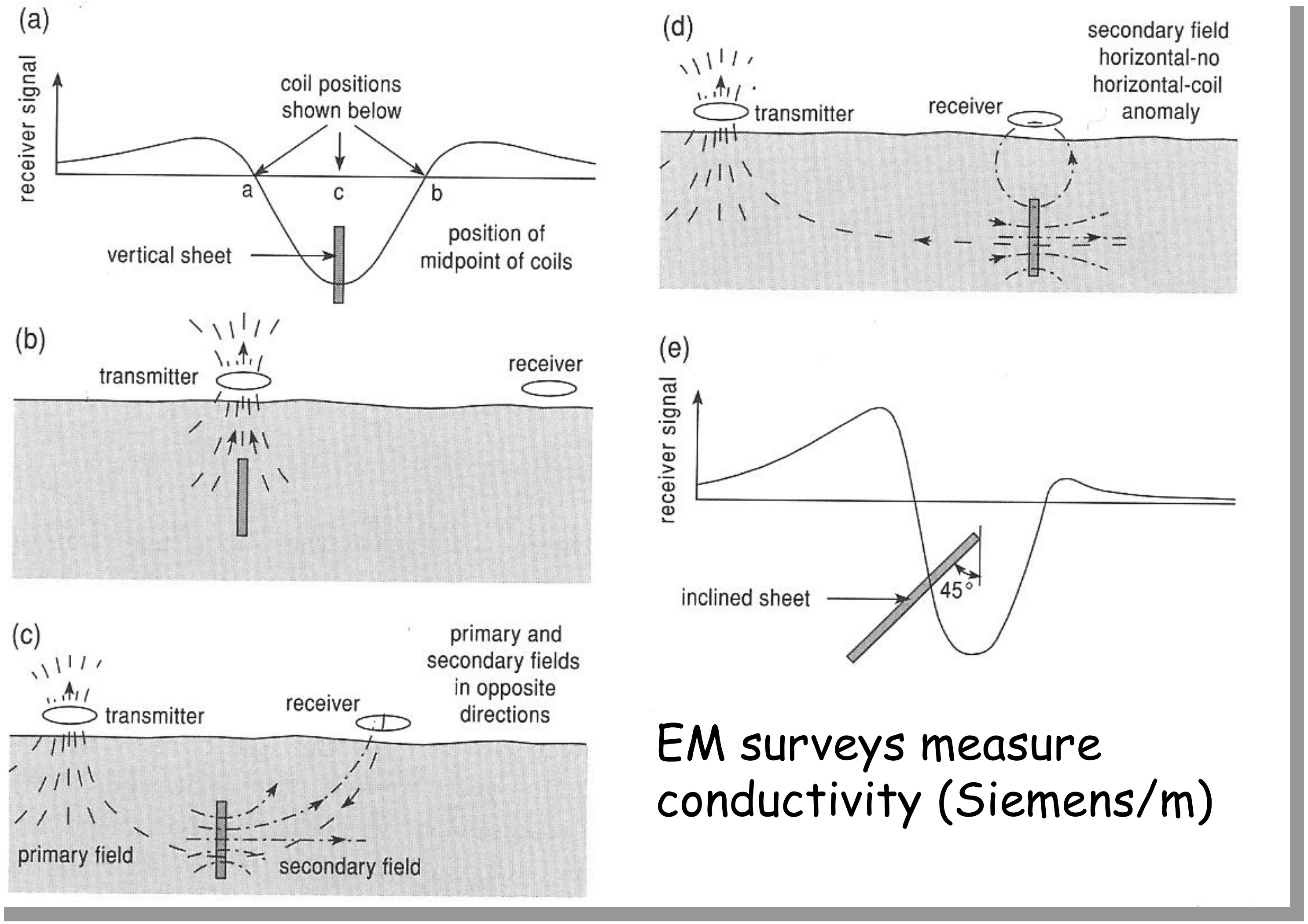
Slingram system: separation kept constant

The contribution by the primary field in the receiver is annihilated so only the secondary field is recorded.

The size of the secondary field is usually given as percentage of primary field.



Example

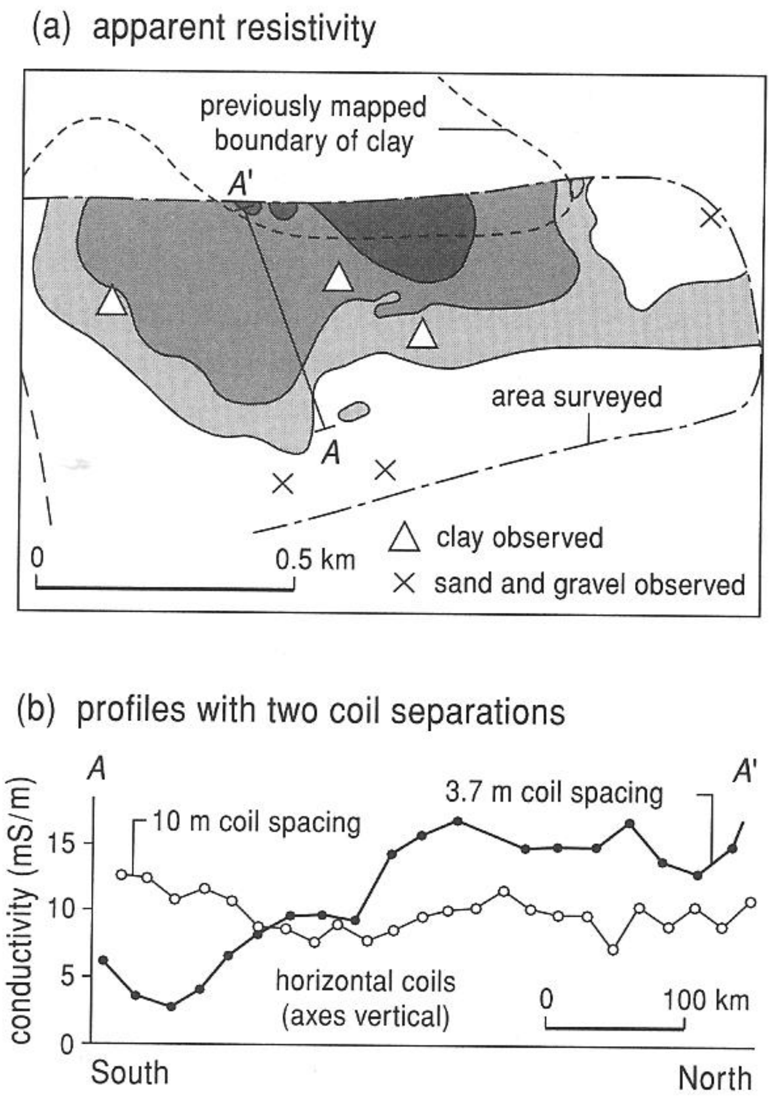


EM surveys measure conductivity (Siemens/m)

Survey

Dark colors depict high conductivity

Deeper clay layer in the south, lower clay layer in the north



Aspects of e-m waves

AC currents generate oscillations that travel just like light, γ-rays, X-rays

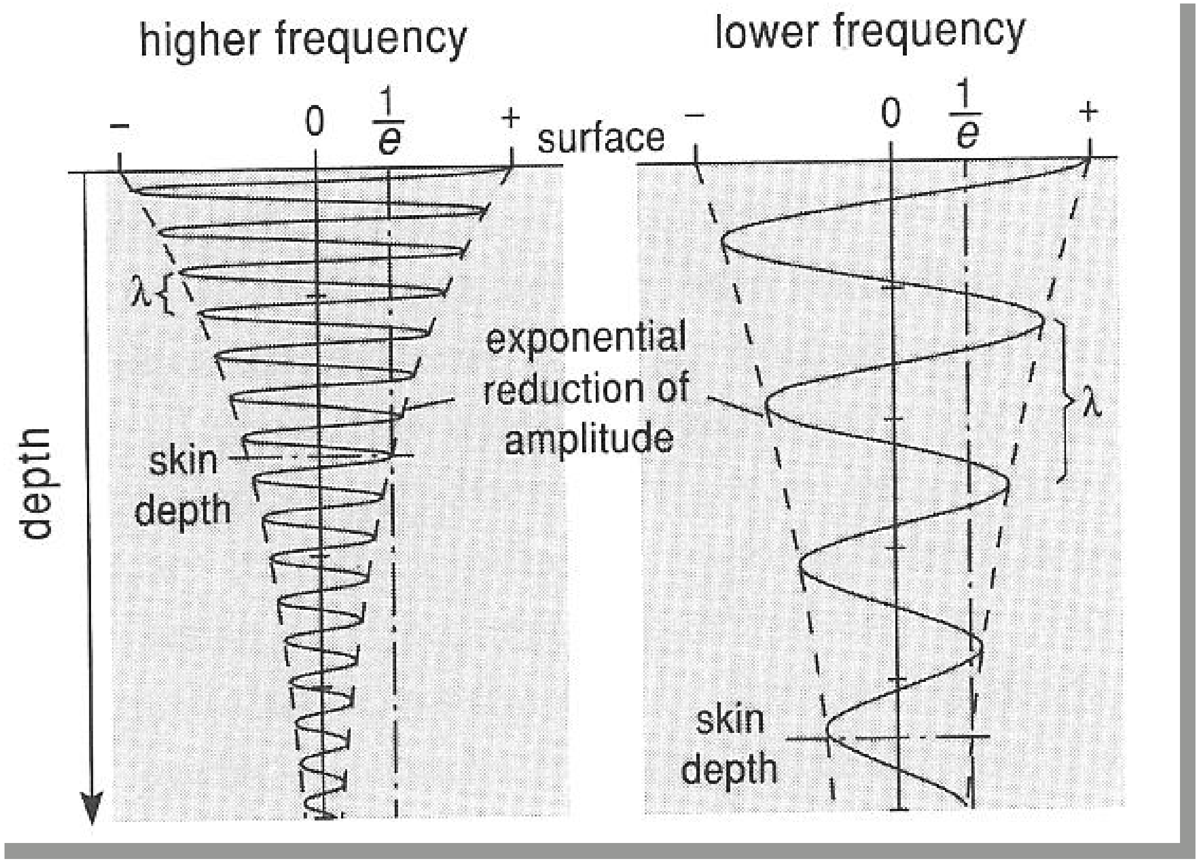
$V = f * \lambda$

V=300.000km/s, f frequency, λ wavelength

Slower velocities in the ground.
Low frequencies (e.g. 1000Hz): field is only time varying

High frequencies (e.g. 1MHz) wave behaviour in space is important (GPR)

Absorbtion



Like in seismic wave propagation em waves loose energy through geometrical spreading. They also loose energy through absorption.

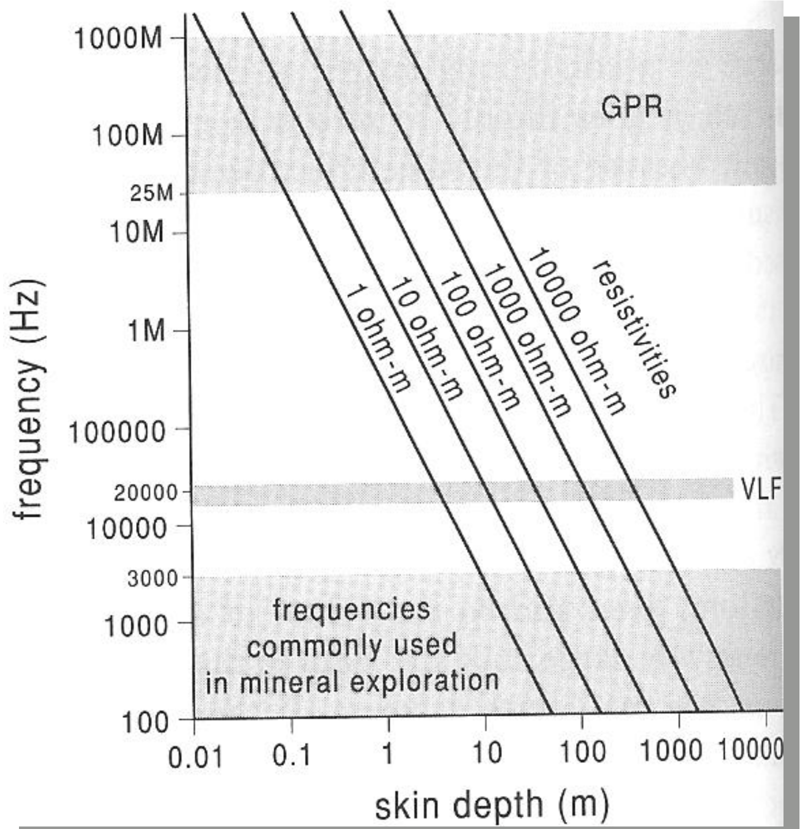
Skin depth

Skin depth d_{skin} is defined as the distance in which the amplitude drops to 1/e (≈1/3)

$$d_{skin} = 500\sqrt{\frac{1}{\sigma f}}$$

High frequency, high conductivity -> shallow skin depth

Low frequency, high resistivity -> large skin depth



Magnetotelluric MT surveys

We need very low frequencies to explore the deep Earth -> use natural currents in the ionosphere. Activity depends on the sun -> magnetic storms.

Frequencies 1/d -> 0.00001 Hz

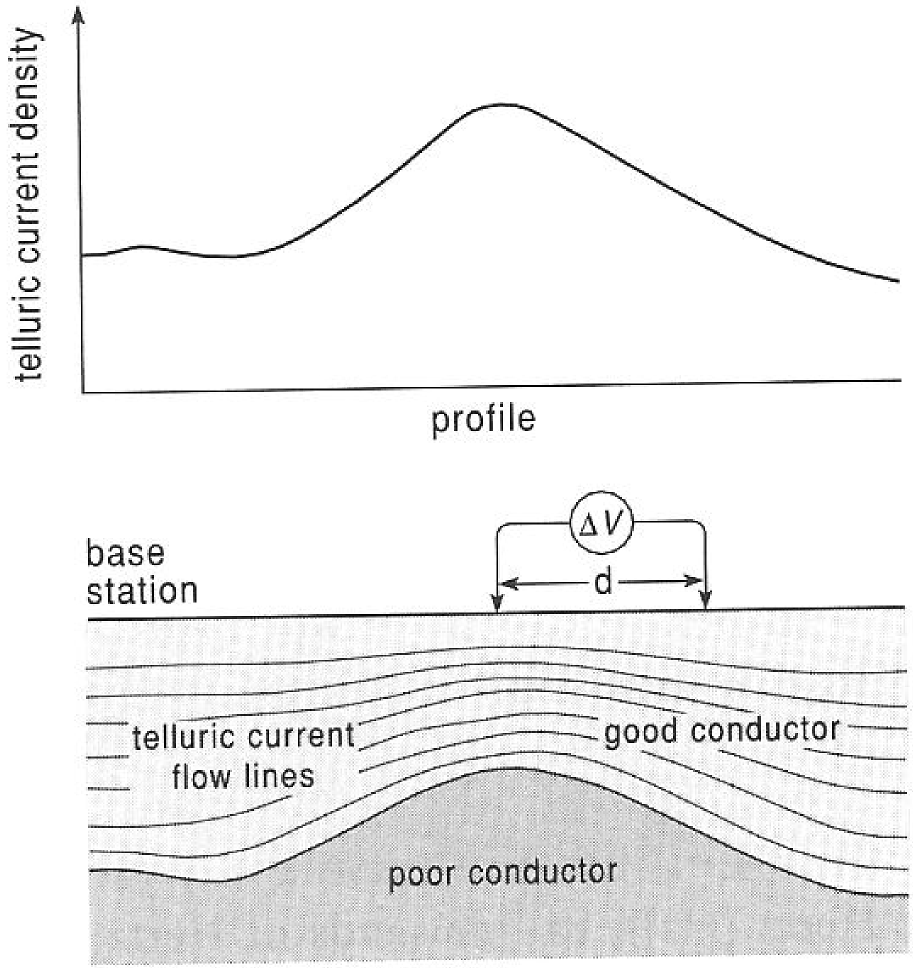
These em waves induce currents in the Earth (telluric), fixed in position relative to the sun (like tides), two maxima a day.

Aim: measure resistivity of subsurface

-> According to Ohm's law a potential difference must exist proportional to the resistance of rock, if a telluric current flows.

Magnetotelluric MT surveys
Principle

Increase of voltage in region with increased current



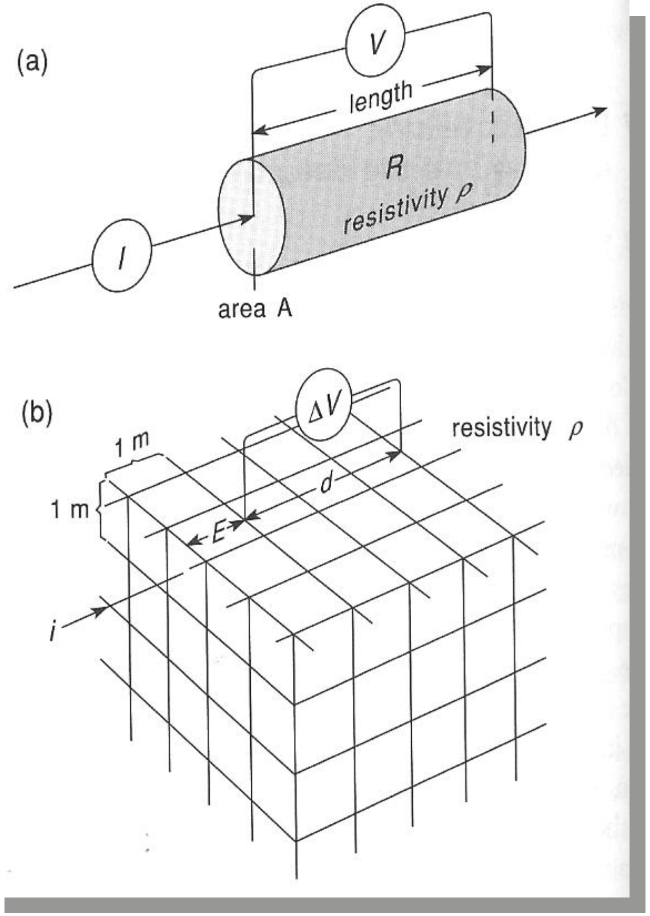
Magnetotelluric MT surveys
Principle

Each cube (1m^3) has resistivity ρ, the resistance being
ρ x length / area = ρ
(for this geometry)

With current i and potential difference E we get

E = ρ i   (equivalent to Ohm's law)

The overall potential difference is
ΔV = E x d
and can be measured as in ordinary resistivity surveys.



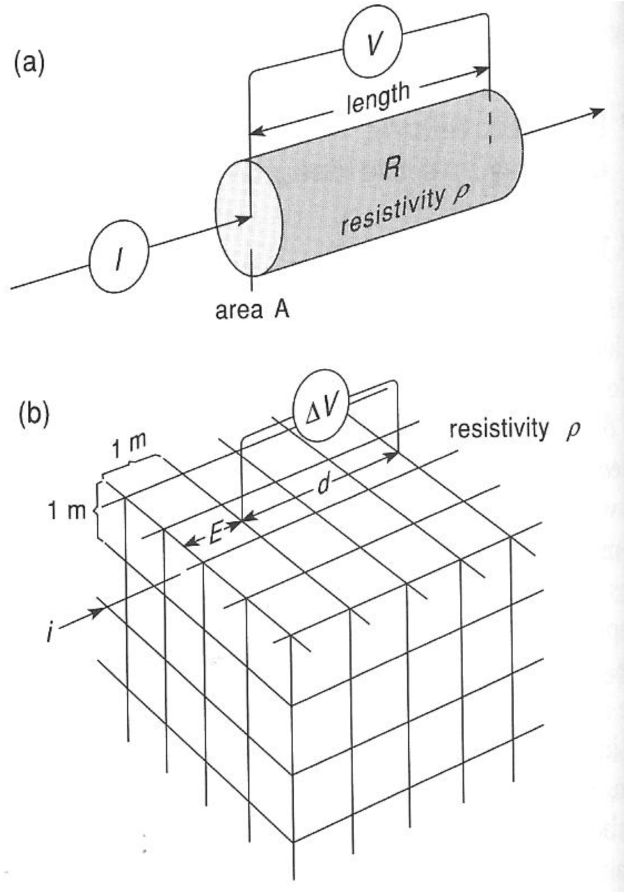
Magnetotelluric MT surveys
the magnetic field

To calculate ρ we need to know the current *i*, which cannot be measured directly. But it creates a magnetic field perpendicular to it.

The (apparent) resistivity can be measured by combining electric field and magnetic field

$$\rho_d = \frac{0.2x10^{-6}}{f}\left(\frac{E}{H}\right)^2$$

E in V/m, H in nT (nanoTesla)

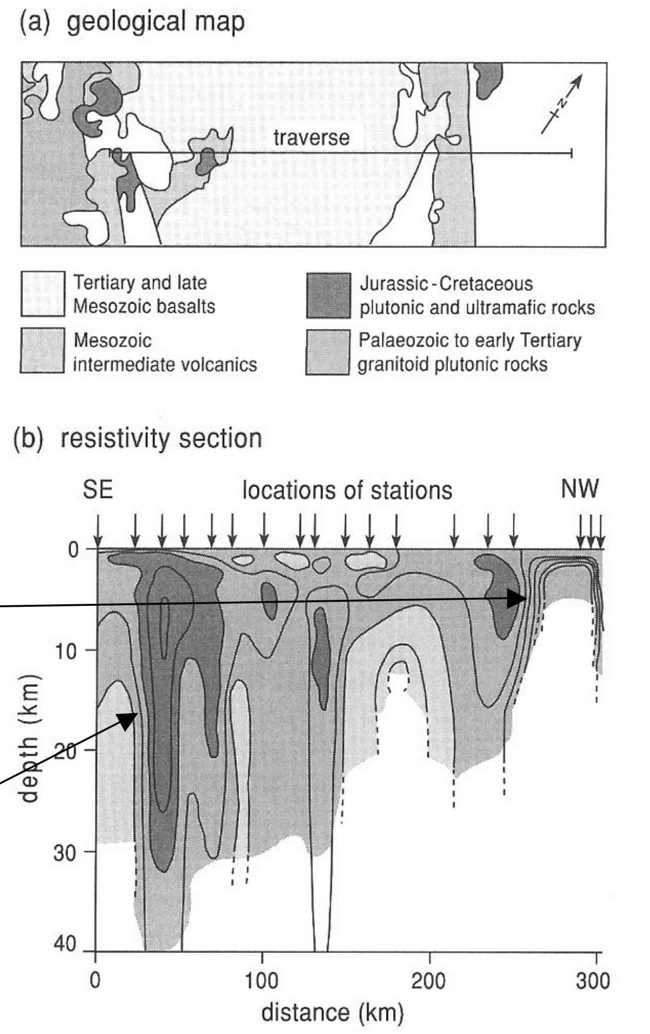


MT survey

- Sounding at 18 sites
- Frequencies from 100Hz to 0.01Hz

Observations:

- Low resistivity near the surface NW (fractured zone, salin waters)
- High resistivity interpreted as plutons

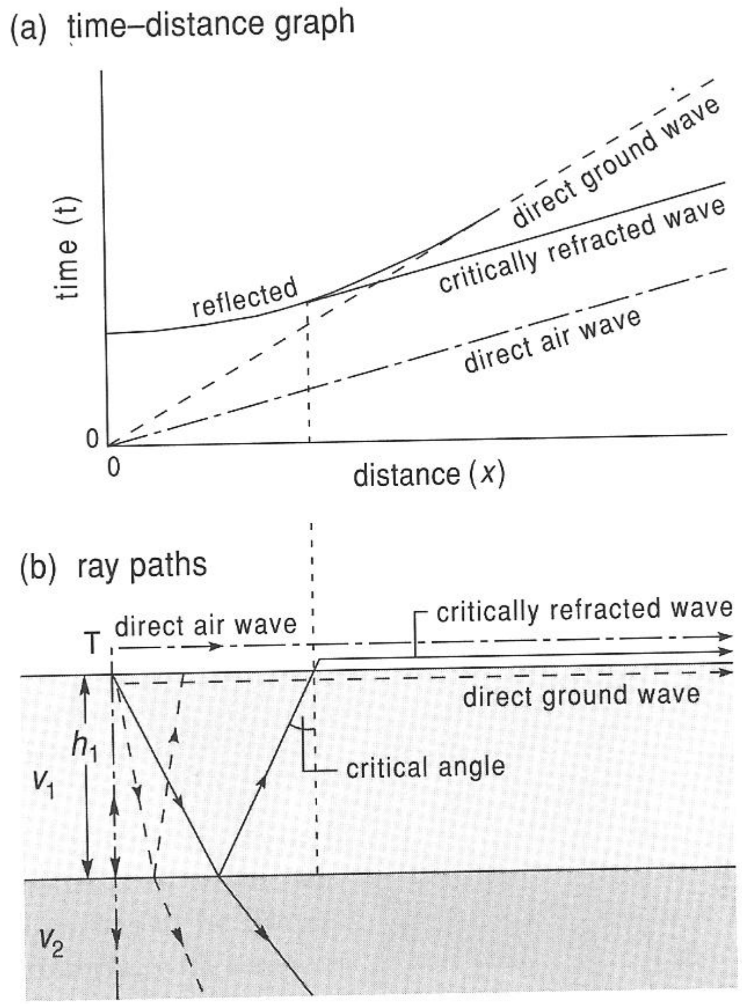


Ground penetrating radar

- Highest frequency of any em method
- Similar to reflection seismics
- Pulse lasts only nanoseconds
- Frequencies 25-1000MHz

-> Wavelength? Travel time?

Observations:
Direct ground wave, air wave,
Refractions at the surface

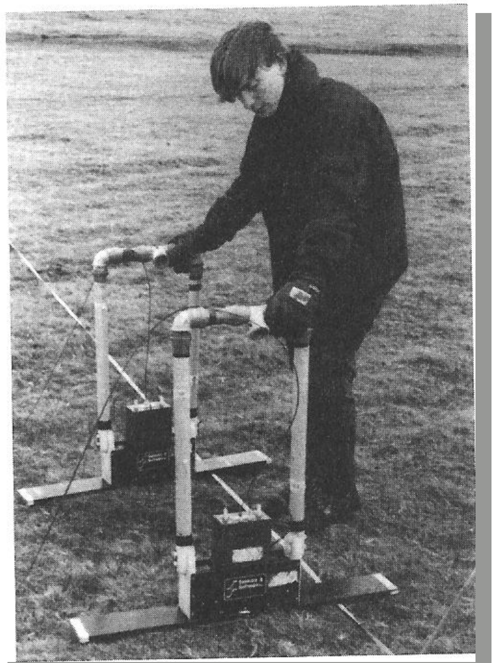


Velocity, reflection

- Wave speed in the ground depends on dielectric constant ε. ε describes the abilty of material to develop positiv and negative charges (like magnetic susceptibility)
- V=c/sqrt(ε) , c light speed
  ε=1 (air)

- Reflection coefficient is given by

$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}} = \frac{v_2 - v_1}{v_2 + v_1}$$



Material parameters

Material	Relative permittivity, ϵ_r	Conductivity, σ (mS/m)	Velocity (m/ns*)	Wavelength (m) at 50 Hz	Wavelength (m) at 1000 Hz
air	1†	0	0.30	6	0.3
water, fresh	81	0.5	0.033	0.66	0.033
water, sea	81	3000	0.01	0.2	0.01
ice, pure	3.2	0.01	0.16	3.2	0.16
clay, wet	25–40	50–100	0.5–0.6	10–12	0.5–0.6
granite	4–6	0.01	0.1–0.12	2–2.4	0.1–0.12
limestone	4–8	0.5–2	0.1–0.12	2–2.4	0.1–0.12
sand, dry	3–6	0.01	0.15	3	0.15
sand, wet	20–30	0.1–1	0.06	1.2	0.06
shale	5–15	1–100	0.09	1.8	0.09
silt	5–30	1–100	0.07	1.4	0.07

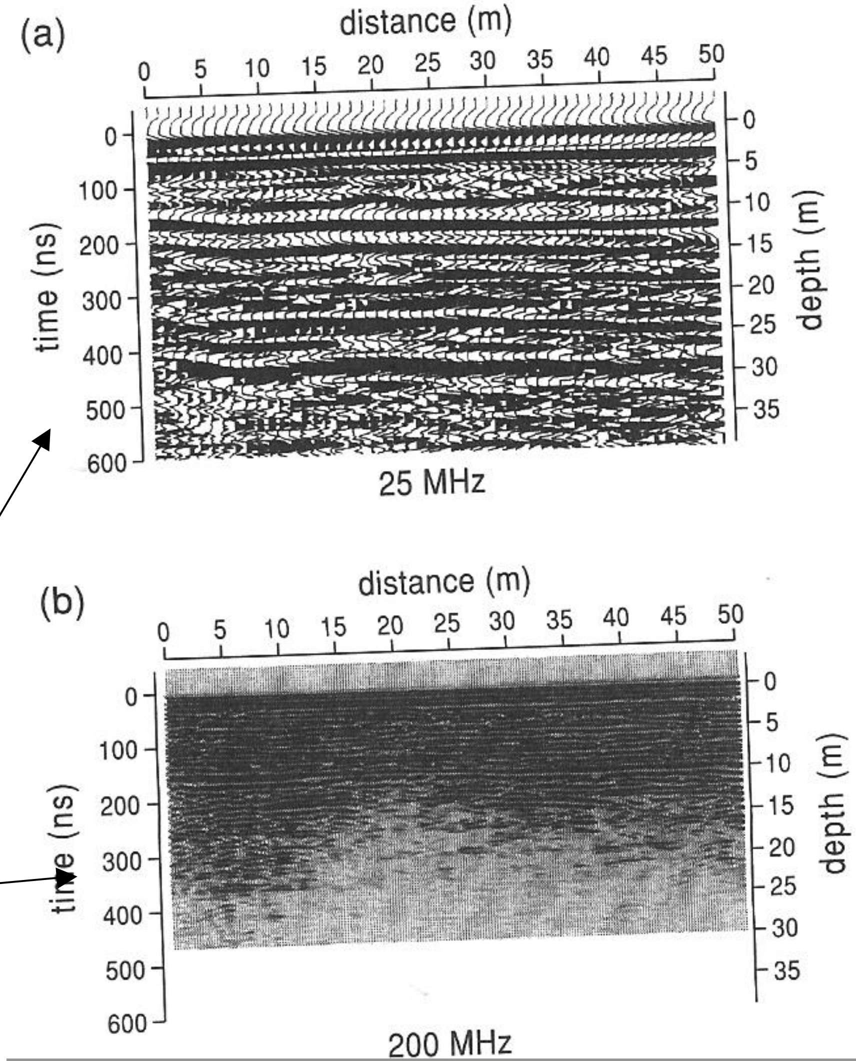
*Because radar waves take such a short time to reach the shallow interfaces, velocities are given in this form (1 ns = 10^{-9} sec).
†All values, which are from various sources, are approximate.

GPR - examples

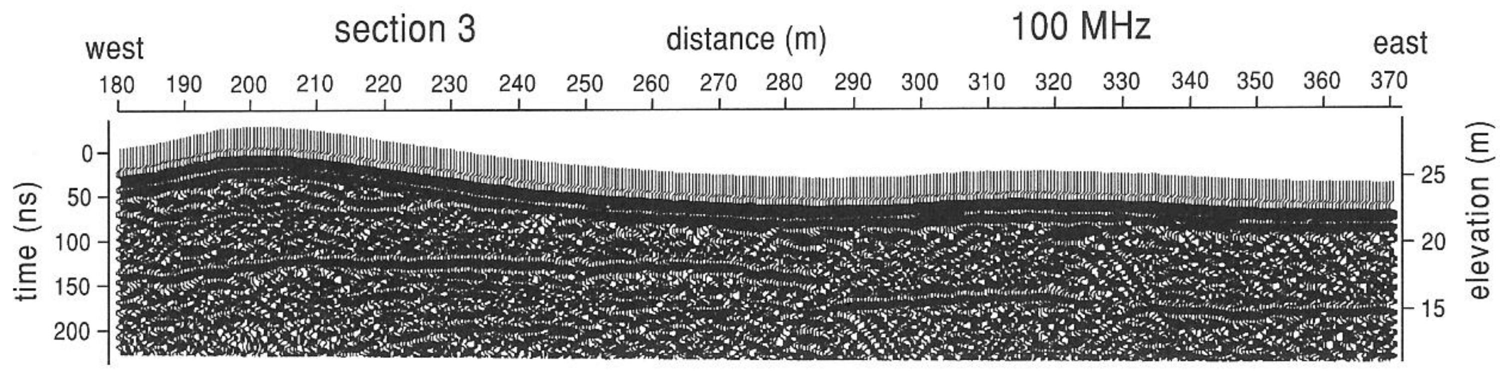
- Penetration depth up to tens of meters
- Only cm in clay or salt water

- Same area imaged with two frequencies

- Lower frequency, -> greater depth range les resolution
- Higher frequency -> better resolution, lower depth range



GPR - examples



- GPR image of a moraine, Netherlands
- Reflectors are water table
- Offsets in horizontal direction
- Artifact or reality?
- Change in velocity or barrier?
- -> probably due to fault

Summary – EM methods

- EM methods aim at imaging the resistivity (or the conductivity) of the subsurface
- EM surveying can be used for aerial surveys (in contrast to resistivity methods)
- The wave nature is most dominant at high frequencies (GPR)
- EM waves are absorbed by conducting rocks and higher frequencies -> penetration depth increases as frequency decreases
- MT (magnetotelluric) surveys use naturally induced currents in the ground, with deep penetration. Resistivities are estimated through measurements of potential differences and the magnetic field as a function of frequencies.
- GPR is the highest resolution method but only applicable for shallow structure, method similar to reflection seismics