Fundamentals of Earth Sciences (ESO 213A)

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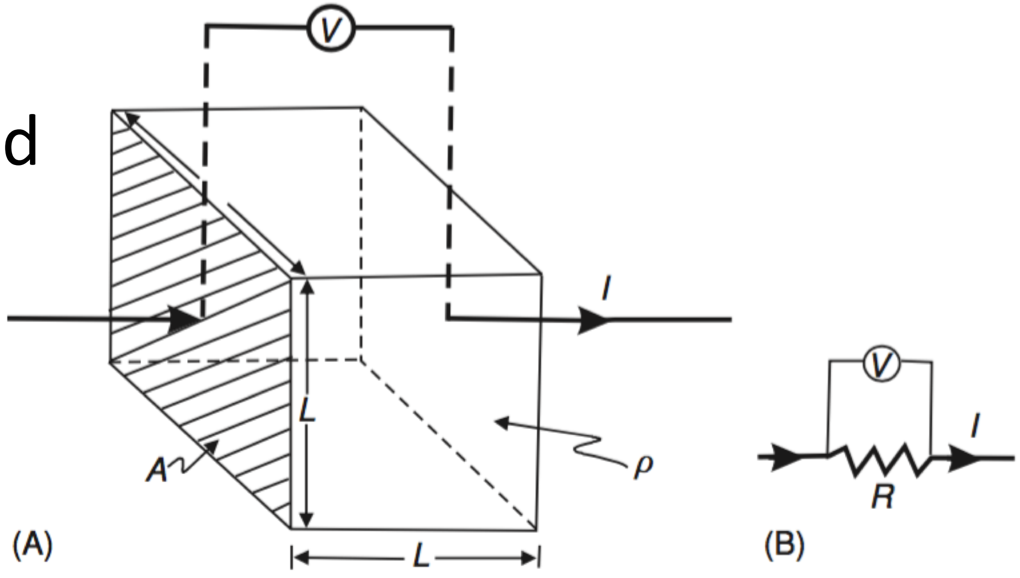
Geophysics: Electrical

Previous Class: Gravity and Magnetic

1. DC Resistivity Method:

Resistance (R) is proportional to length (L) divided by area (A): $R \propto L/A$. This can be written as $R = \rho L/A$, where ρ is the true resistivity.



Ohm's Law

For an electrical circuit, Ohm's Law gives $R = V/I$, where V and I are the potential difference across a resistor and the current passing through it, respectively. This can be written alternatively in terms of the electric field strength (***E***; volts/m) and current density (***J***; amps/m^2) as:

$\rho = \boldsymbol{E}/\boldsymbol{J}$ (ohm-m) Resistivity is defined by:

$\rho = VA$ (ohm-m)

Ways of electric current flow :

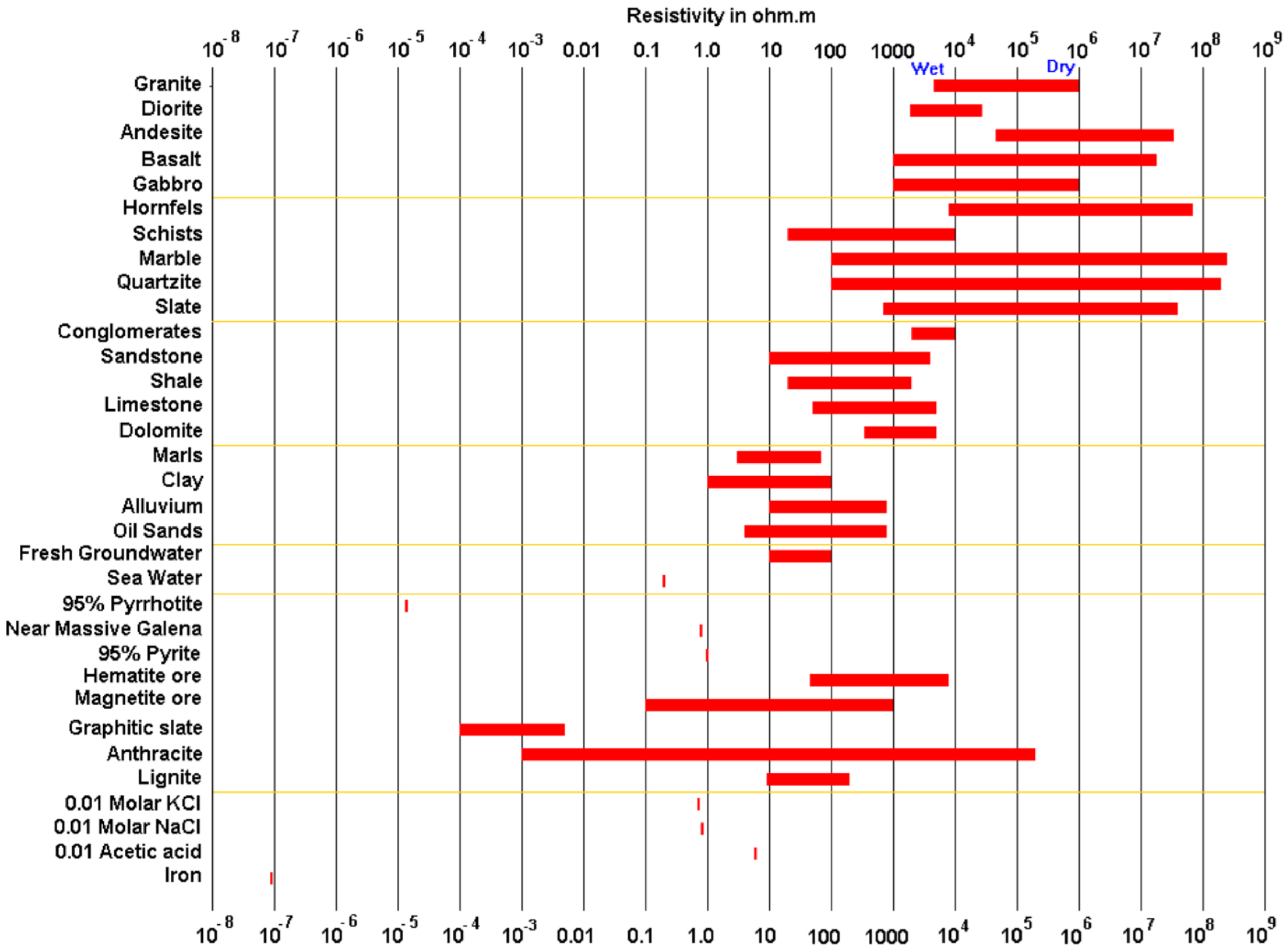
- There are three ways in which electric current can be conducted through a rock: electrolytic, electronic (ohmic) and dielectric conduction.
- *Electrolytic conduction* occurs by the relatively slow movement of ions within an electrolyte and depends upon the type of ion, ionic concentration and mobility.
- *Electronic conduction* is the process by which metals, for example, allow electrons to move rapidly, so carrying the charge.
- *Dielectric conduction* occurs in very weakly conducting materials (or insulators) when an external alternating current is applied, so causing atomic electrons to be shifted slightly with respect to their nuclei.

- In most rocks, conduction is by way of pore fluids acting as electrolytes, with the actual mineral grains contributing very little to the overall conductivity of the rock (except where those grains are themselves good electronic conductors).

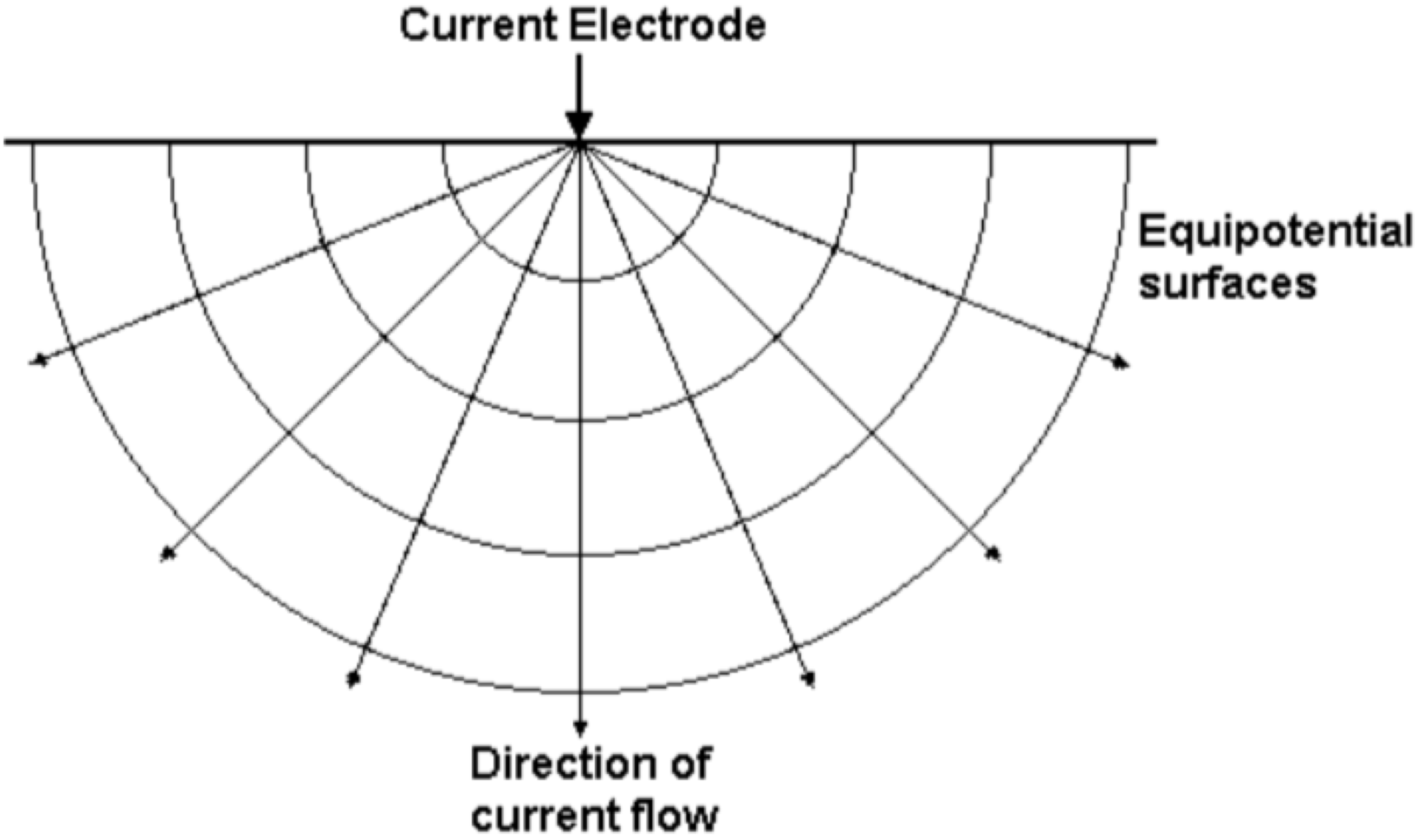
Resistivity of rocks :

- The resistivity of geological materials exhibits one of the largest ranges of all physical properties, from 1.6 × 10^{-8} ohm-m for native silver to 10^{16} ohm-m for pure sulphur.
- Igneous rocks tend to have the highest resistivities.
- Sedimentary rocks tend to be most conductive, largely due to their high pore fluid content.
- Metamorphic rocks have intermediate but overlapping resistivities.
- The age of a rock is also an important consideration: a Quaternary volcanic rock may have a resistivity in the range 10–200 ohm-m, while that of an equivalent rock but Precambrian in age may be an order of magnitude greater. This is a consequence of the older rock having far longer to be exposed to secondary infilling of interstices by mineralisation, and compaction decreasing the porosity and permeability

- Saline groundwater may have a resistivity as low as 0.05 ohmh-m and some groundwater and glacial meltwater can have resistivities in excess of 1000 ohm-m.

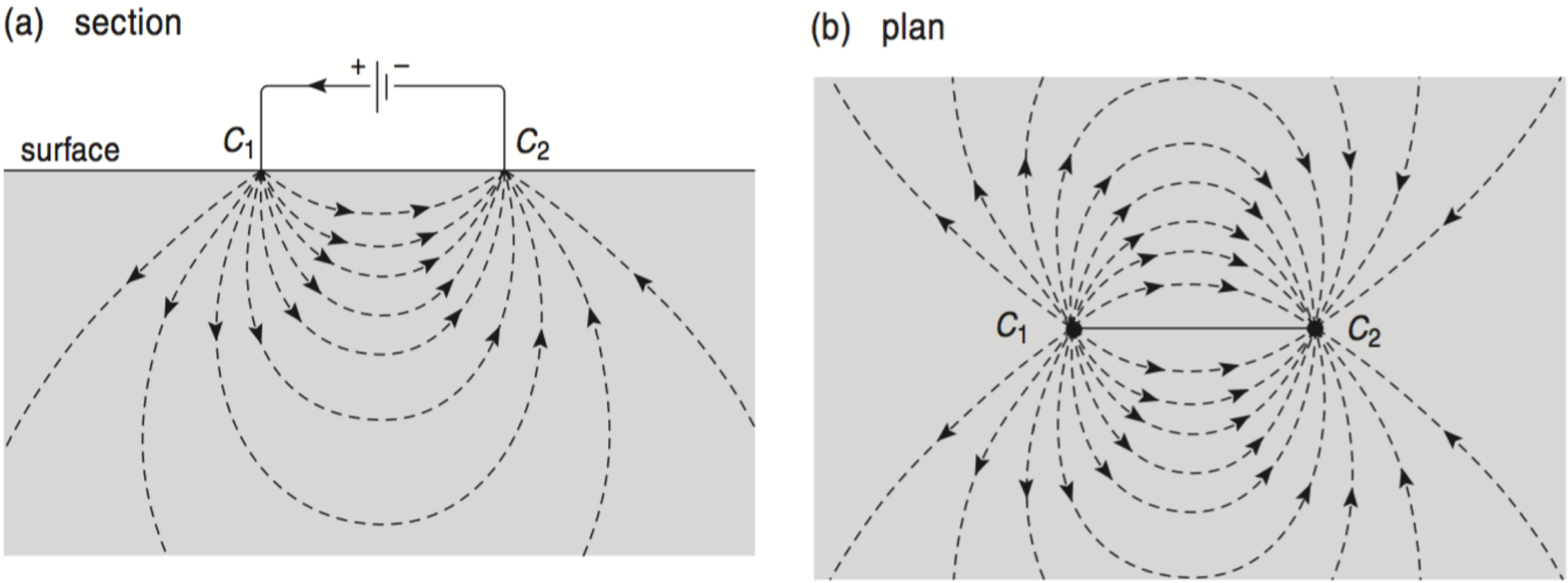

Resistivity in ohm.m
Wet
Dry
Granite
Diorite
Andesite
Basalt
Gabbro
Hornfels
Schists
Marble
Quartzite
Slate
Conglomerates
Sandstone
Shale
Limestone
Dolomite
Marls
Clay
Alluvium
Oil Sands
Fresh Groundwater
Sea Water
95% Pyrrhotite
Near Massive Galena
95% Pyrite
Hematite ore
Magnetite ore
Graphitic slate
Anthracite
Lignite
0.01 Molar KCl
0.01 Molar NaCl
0.01 Acetic acid
Iron
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 0.01 0.1 1.0 10 100 1000 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9}

Current flow for a point charge

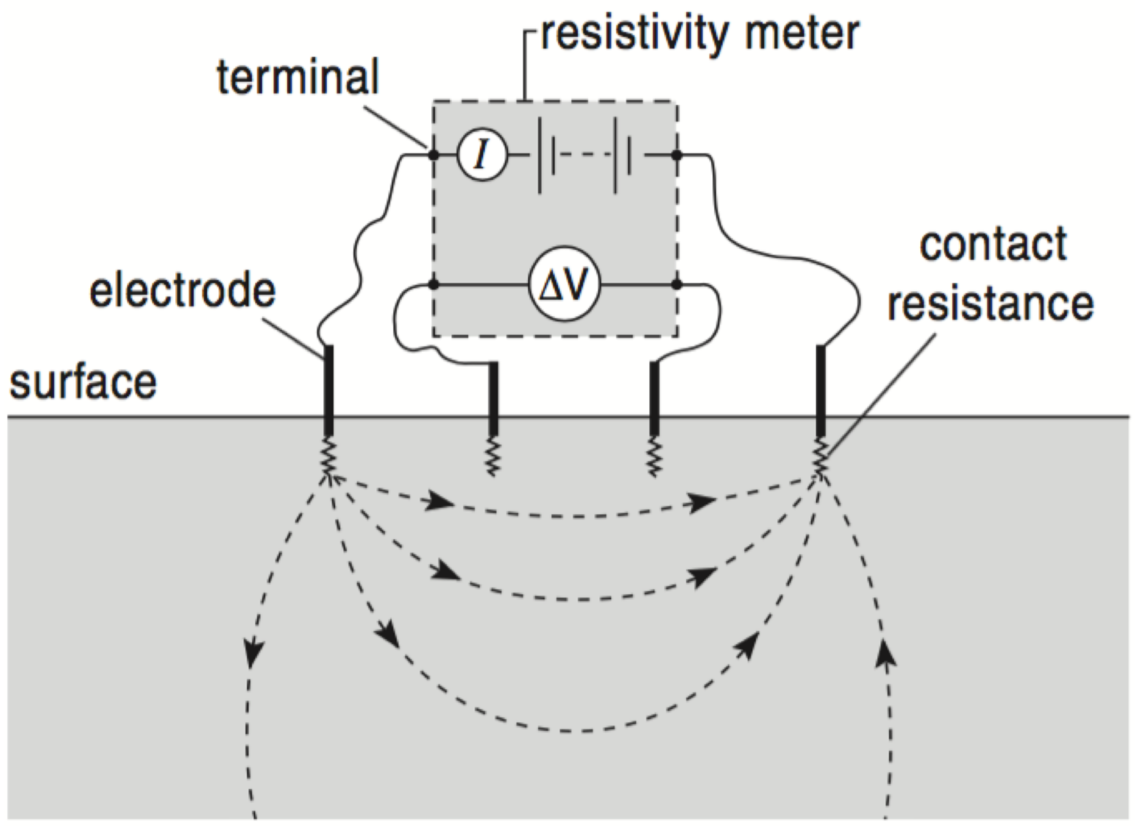


Current path

- Electrical connections are made through **electrodes,** metal rods pushed a few centimetres into the ground. Two current electrodes are used, *C*1 and *C*2, current flowing in at one and out at the other.
- In uniform ground, only about 30% of the current penetrates below a depth equal to the separation of the current electrodes.

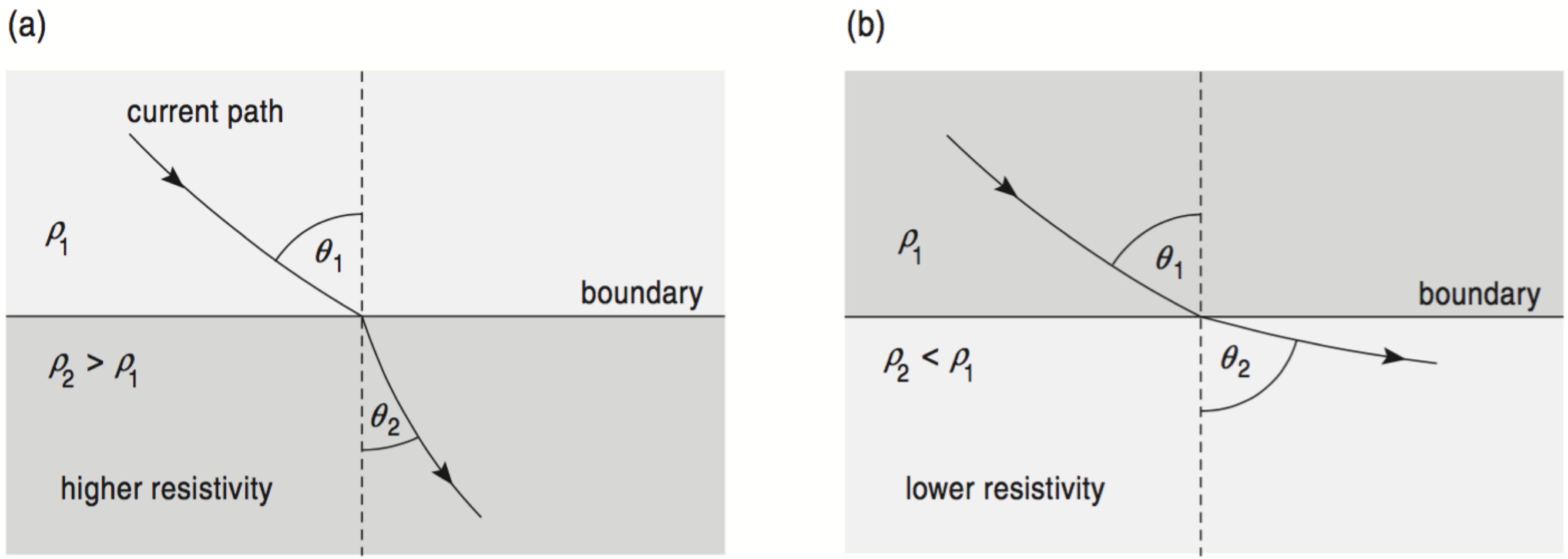


- The power supply (usually run from batteries except for very large-scale surveys, where generators are used)
- Current meter, and voltmeter are usually combined into a single instrument, a **resistivity meter,** which often displays the ratio $\Delta V/I$ rather than the quantities separately.
- It is connected to the electrodes by wires whose resistances are very small.
- The voltage applied to the current electrodes is typically about 100 volts, but the current is only milliamps or less (sufficient to give a shock but not be dangerous) and ΔV ranges from volts to millivolts.



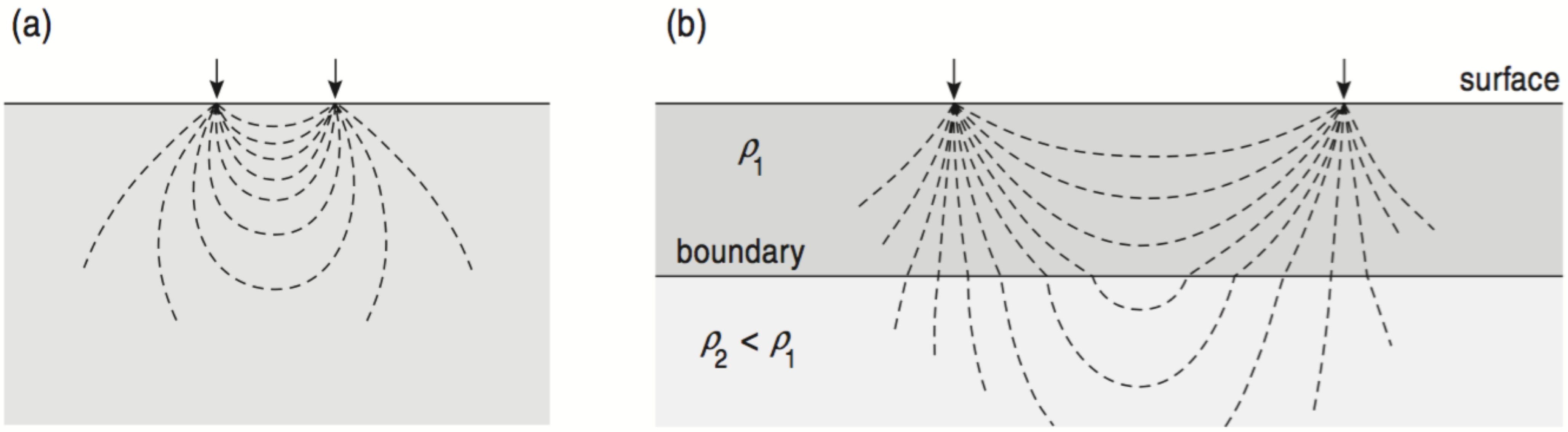
Refraction of current paths

- Within a uniform layer the current paths are smooth curves, but they bend, or refract, as they cross an interface separating different resistivities. They refract towards the normal when crossing into rock with higher resistivity, and conversely in rock with lower resistivity.
- (There are similarities with refraction of seismic rays, but the angles of current lines are related by $\rho 1 \tan \theta 1 = \rho 2 \tan \theta 2$, not sine as in Snell's Law, and seismic rays refract away from the normal when crossing into rock with higher seismic velocity.)



Vertical electrical sounding (VES)

- Also called as depth sounding or sometimes electrical drilling – is used when the subsurface approximates to a series of horizontal layers, each with a uniform but different resistivity.
- In a VES survey, $\Delta V/I$, is measured with increasing electrode separations. This ratio changes for two reasons, because of changes of resistivity with depth but also simply because the electrodes are being moved apart.



Wenner VES survey

Two measuring tapes are laid out end to end and four electrodes are pushed into the ground at equal intervals, symmetrically about the junction of the tape measures; they are connected to the resistivity meter, and readings are taken. The electrode separation is then increased and the expansion is stopped when the current is judged to have penetrated deep enough, roughly half the separation of the current (outer) electrodes.

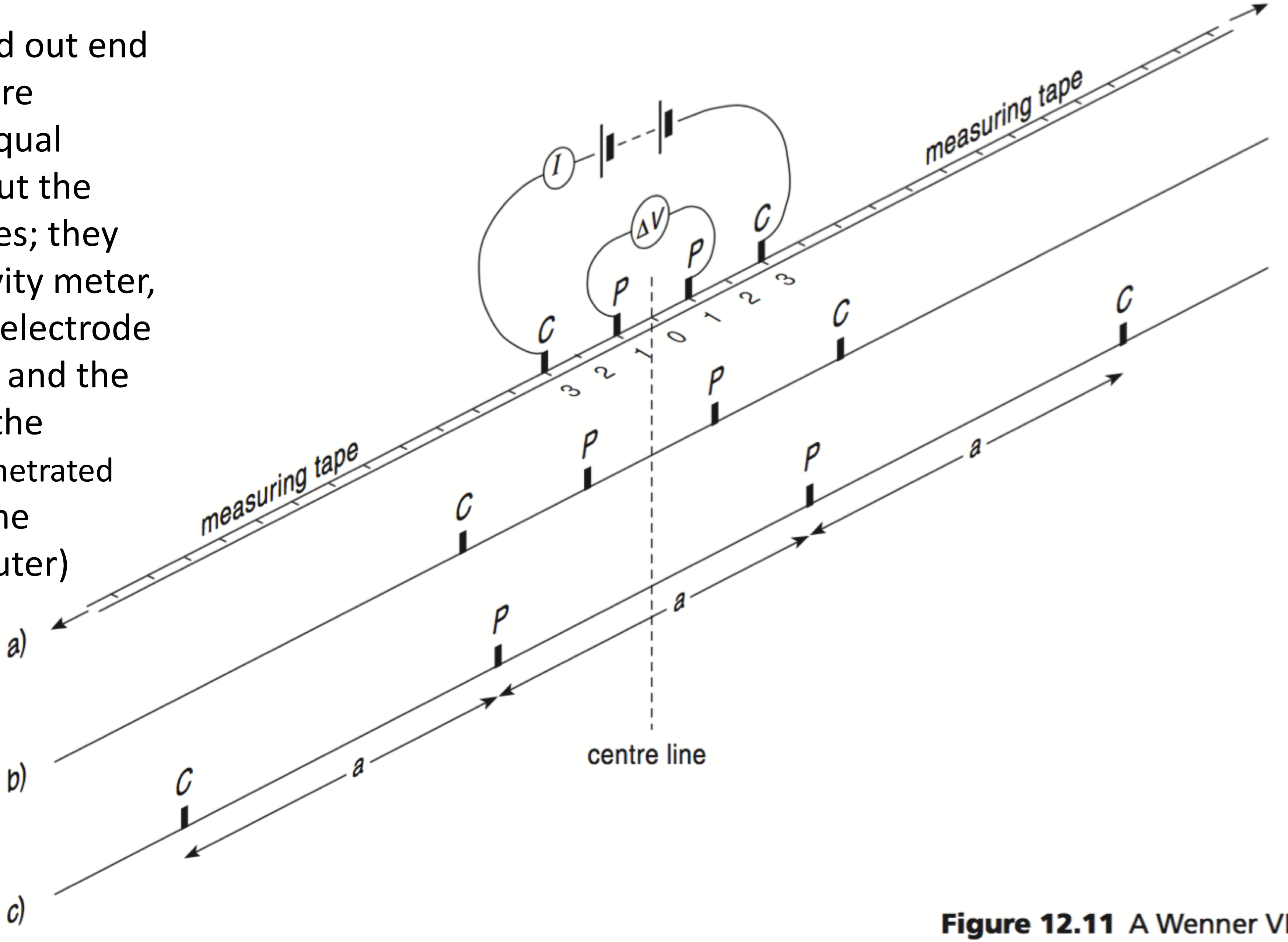
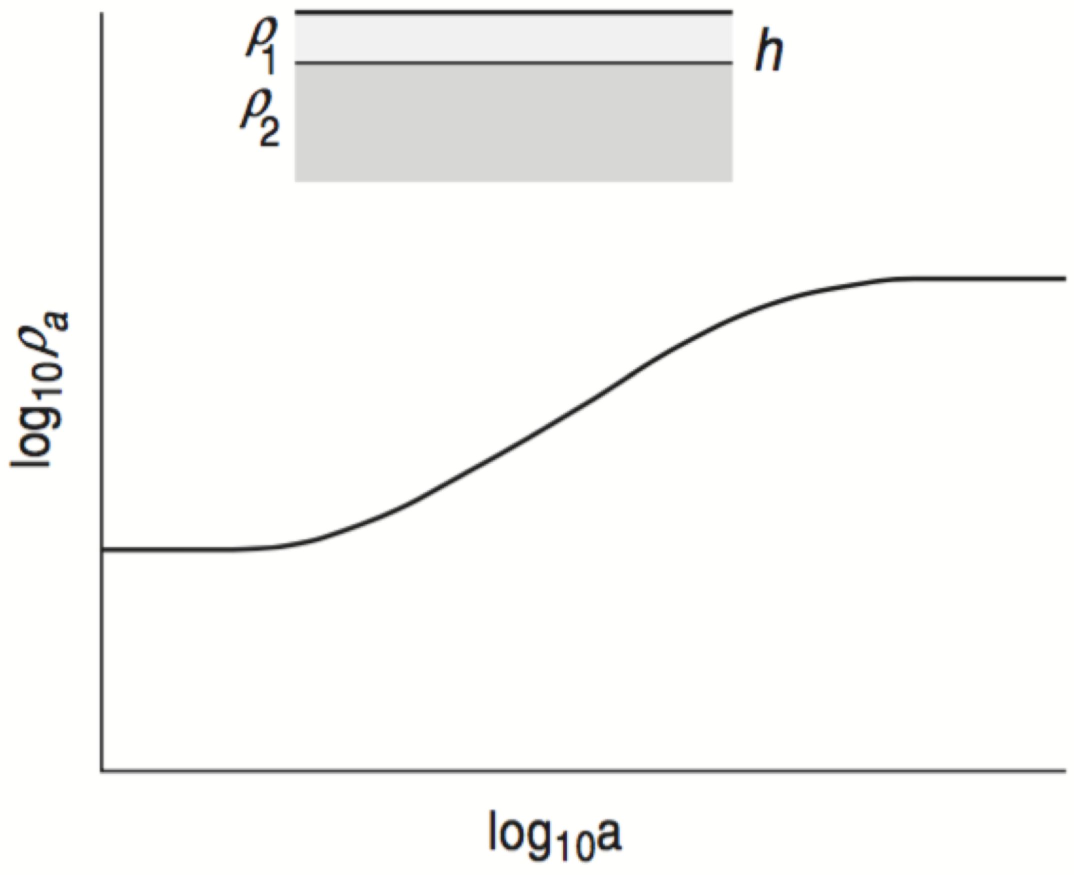
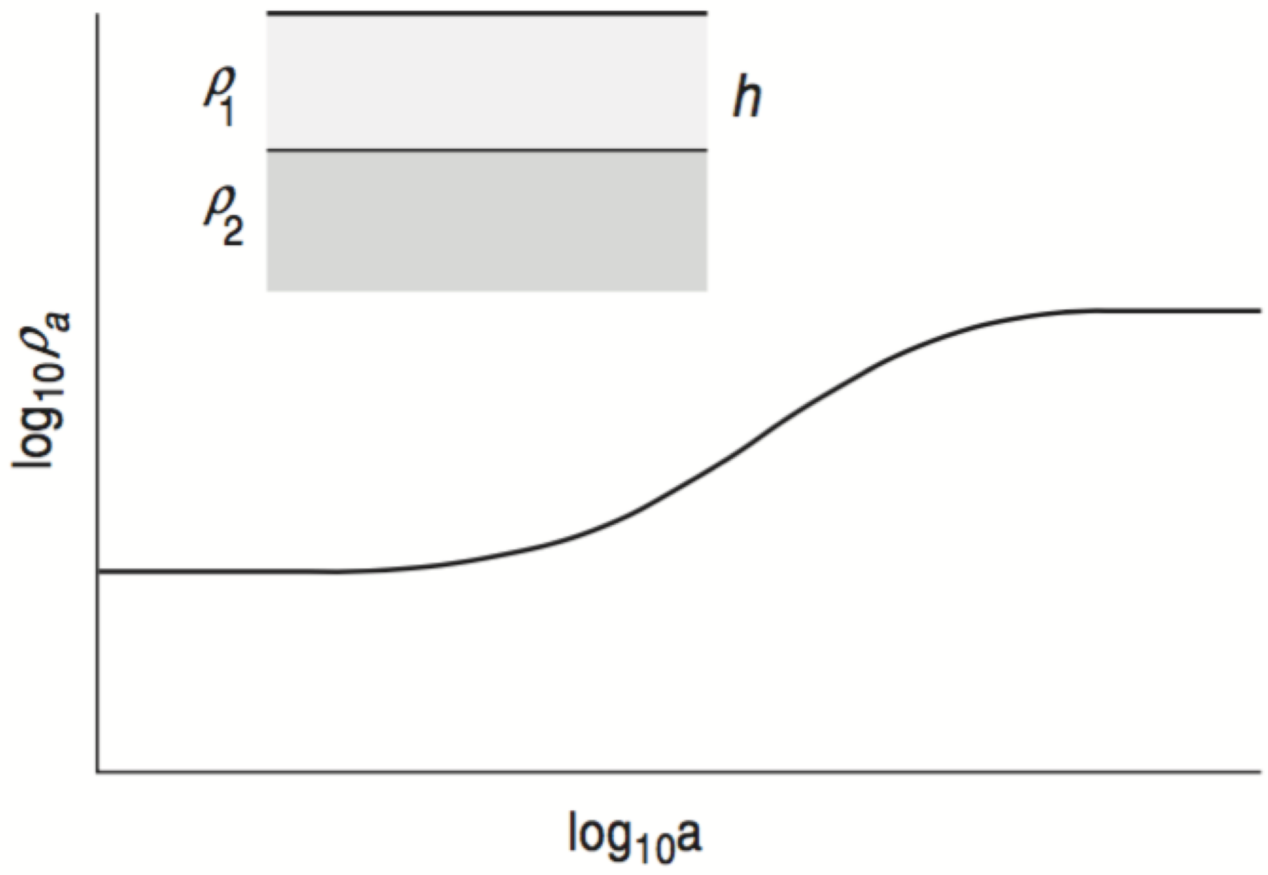


Figure 12.11 A Wenner VES survey.

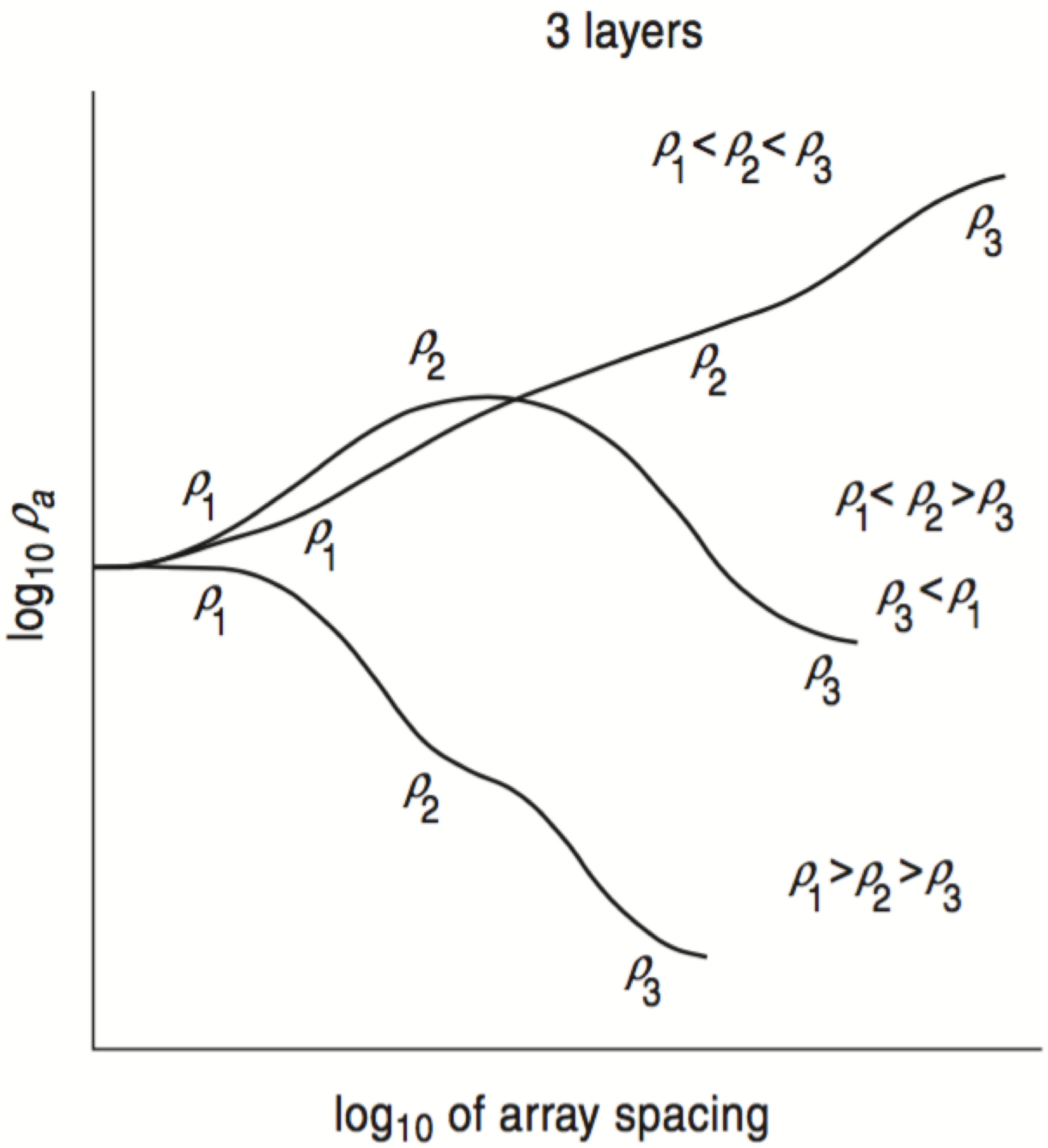
Wenner array

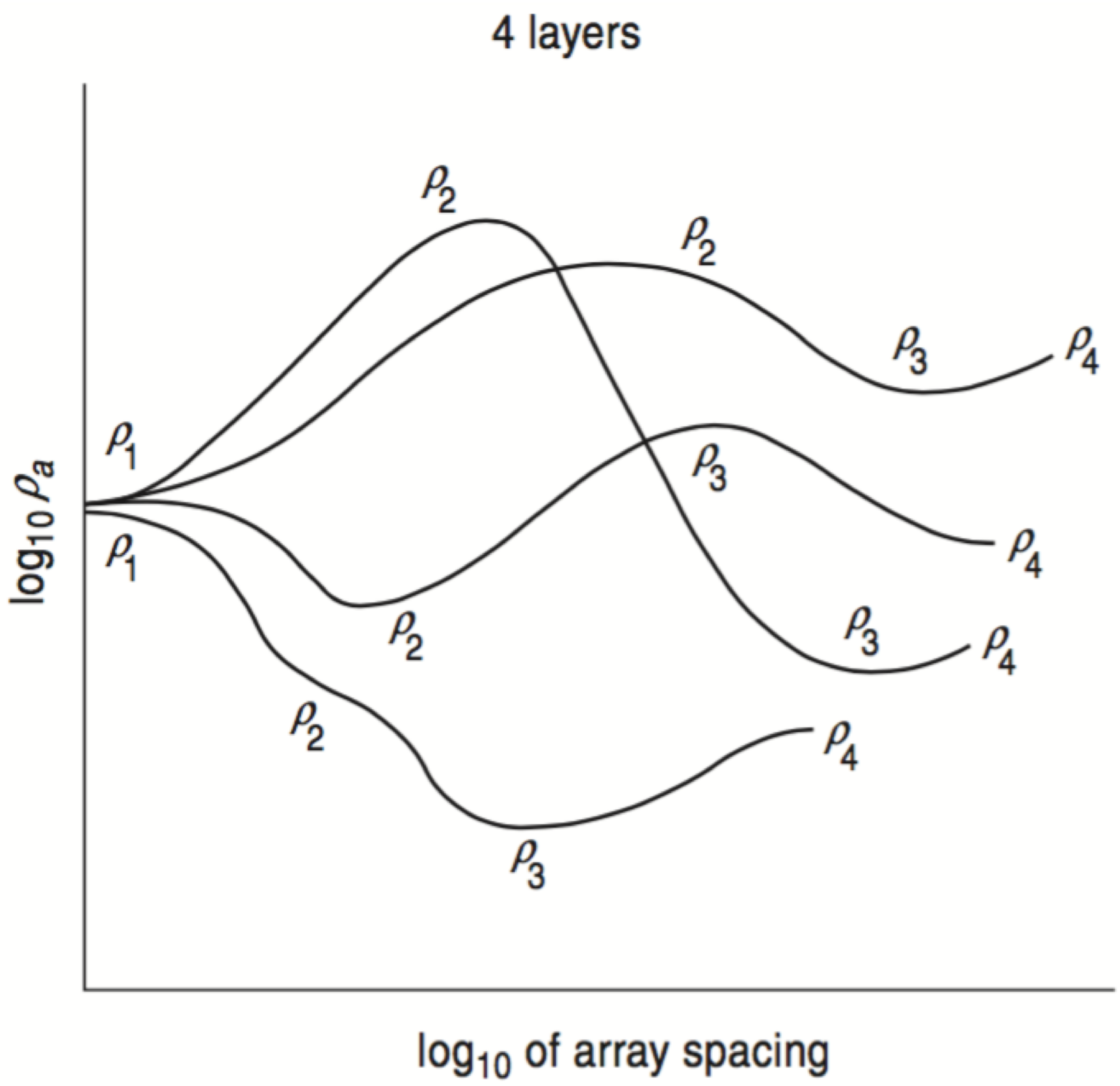




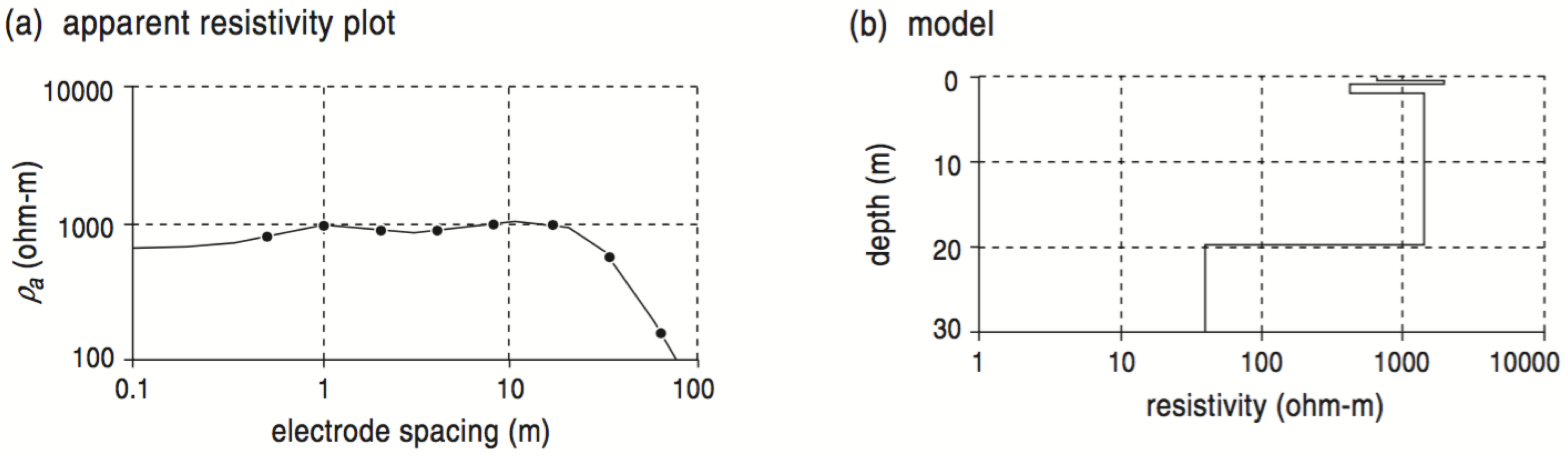
Apparent resistivity is calculated for each spacing, using $\rho_a = 2\pi a \, \Delta V/I$, and a graph is plotted of $\log_{10}\rho$ versus $\log_{10}a$

Multi layer cases



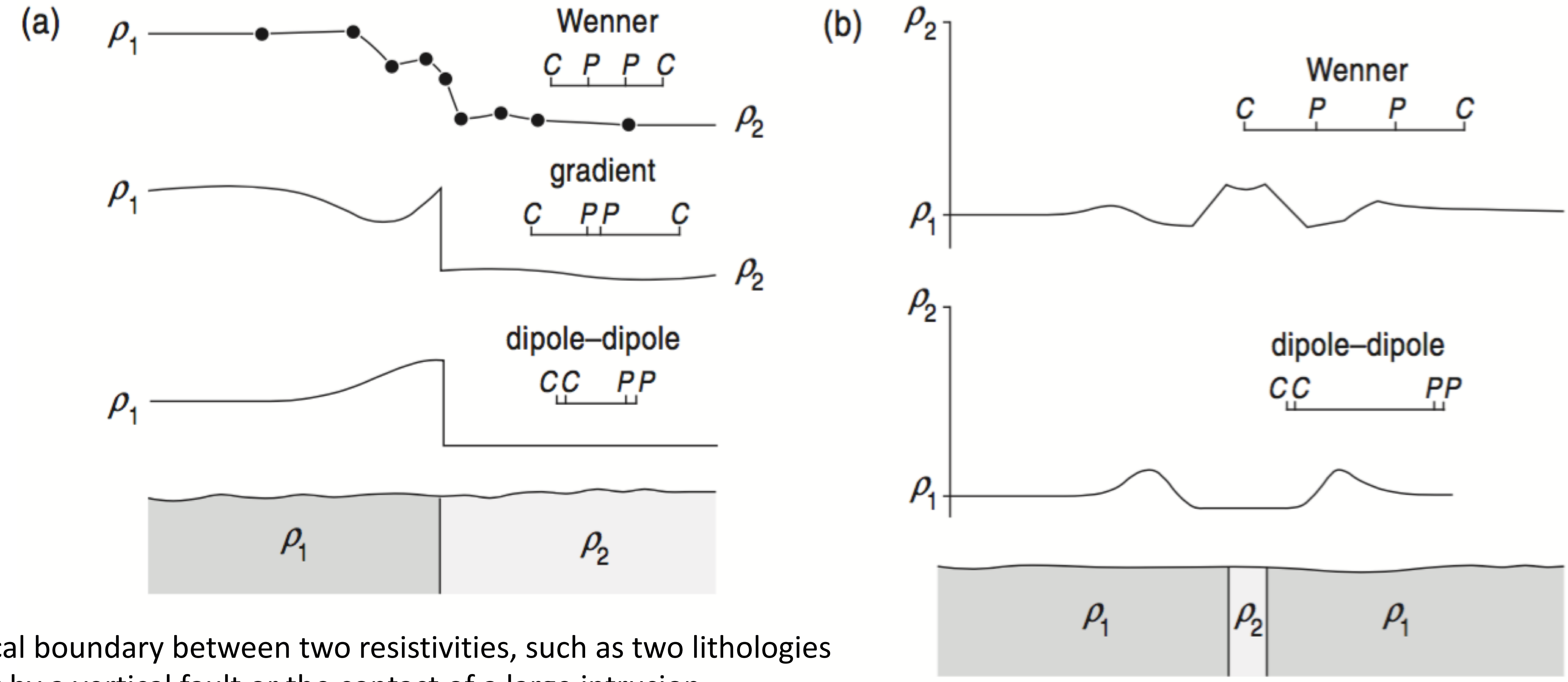


Modelled Multi Layer



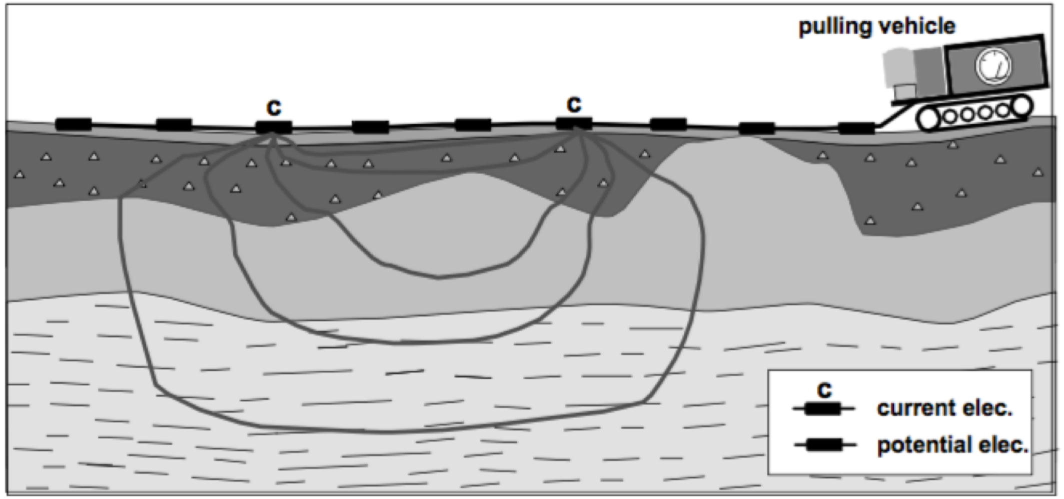
Resistivity profiling:

Vertical electrical sounding (VES) investigates how resistivity varies with depth, assuming layers with no lateral variation; in contrast, **electrical profiling** investigates lateral changes, such as the presence of a mineral vein or a geological boundary. Whereas VES 'expands' an array symmetrically about a point, in profiling some or all the electrodes are moved laterally with fixed spacing.



Vertical boundary between two resistivities, such as two lithologies offset by a vertical fault or the contact of a large intrusion

Resistiviy Imaging Survey



The Aarhus Pulled Array System. The system shown has two current (C) electrodes and six potential electrodes (Christensen and Sørensen 1998, Bernstone and Dahlin 1999).

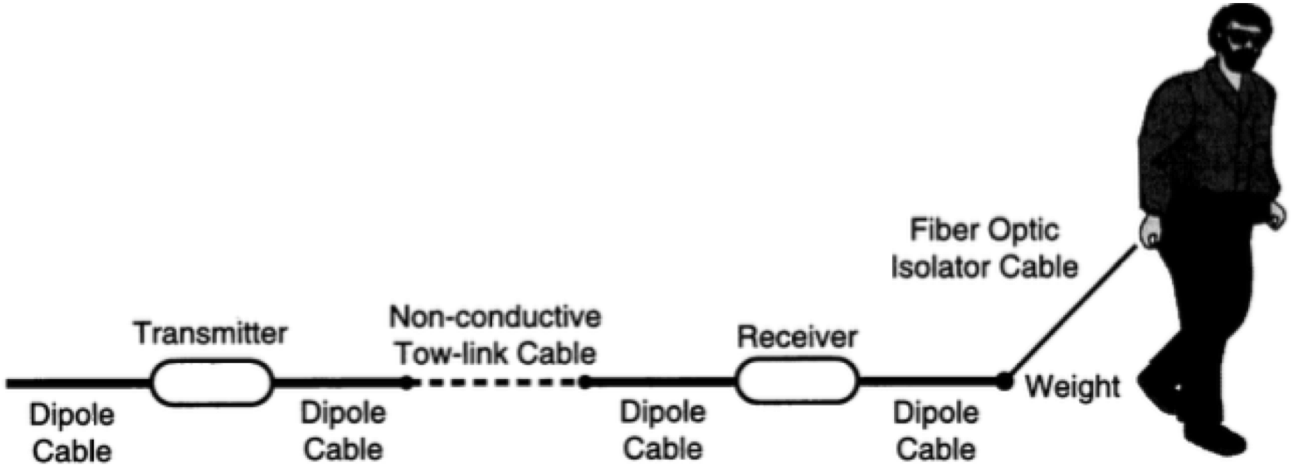


Figure 2.5. The Geometrics OhmMapper system using capacitive coupled electrodes. (Courtesy of Geometrics Inc.)

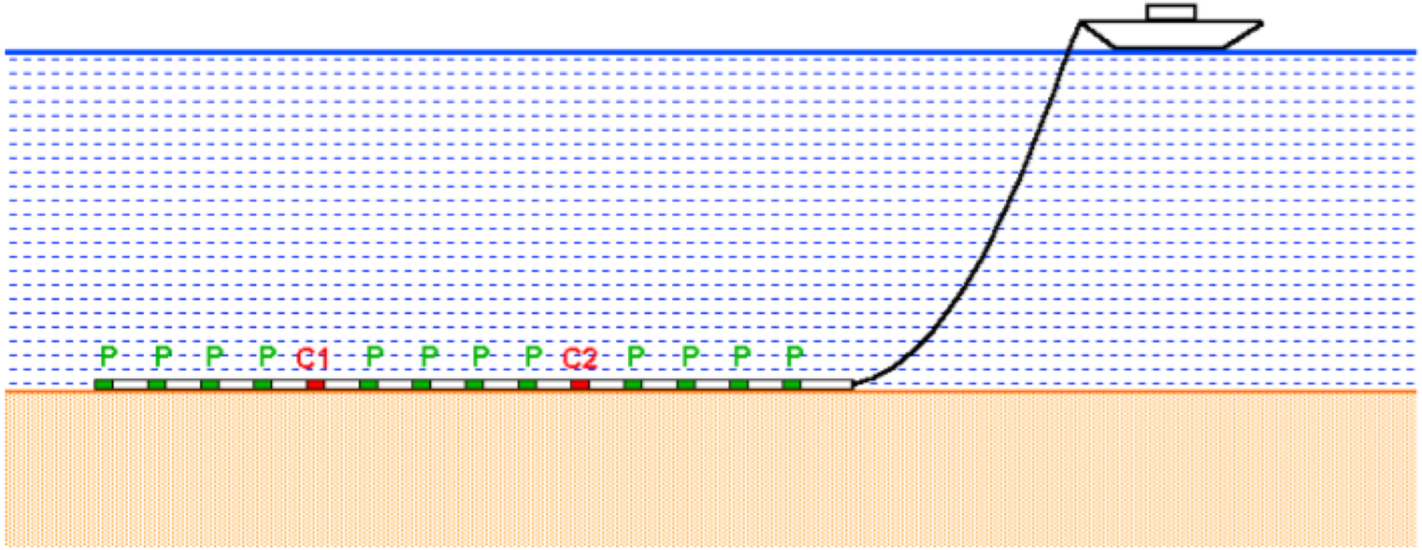
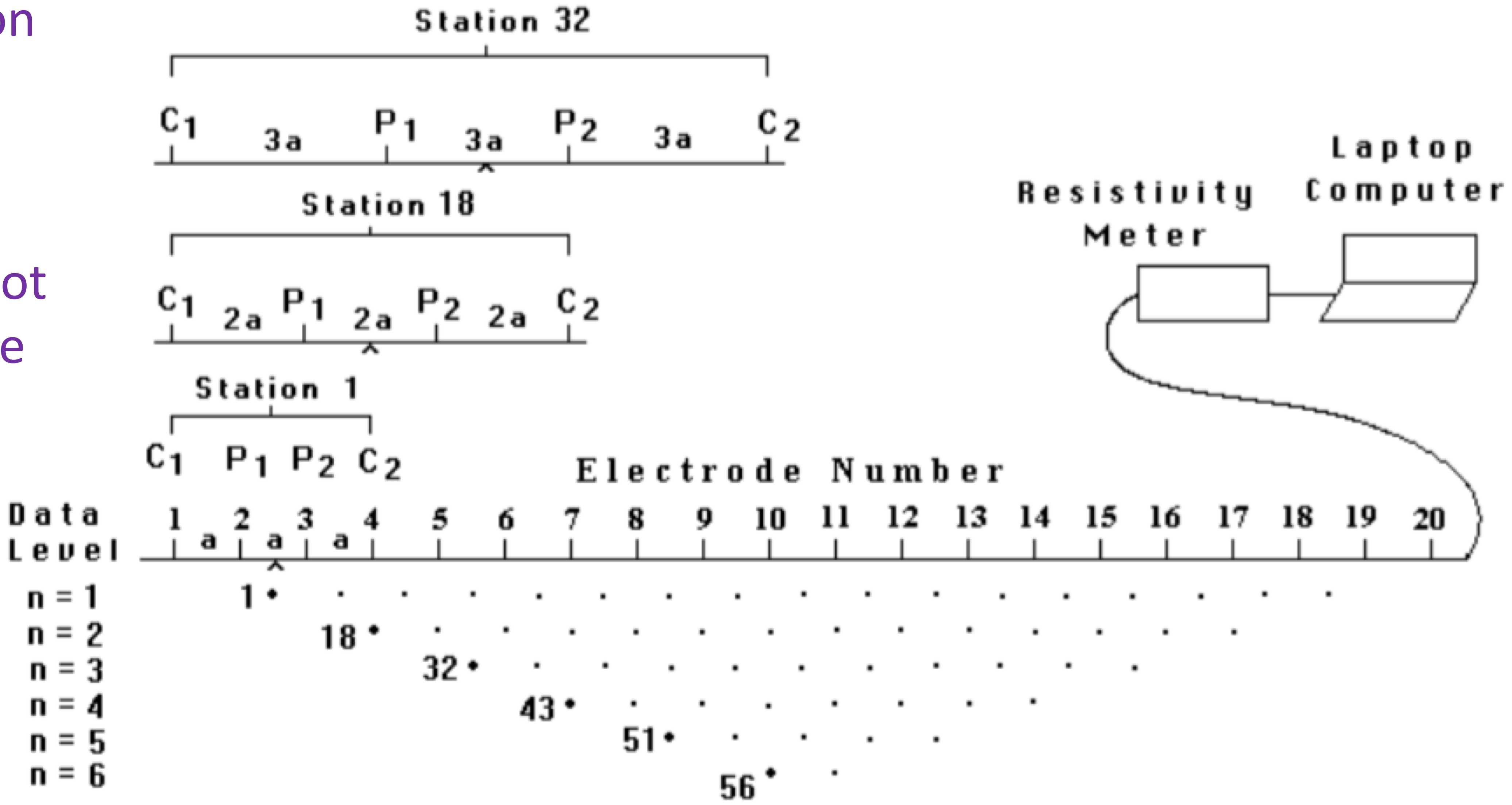


Figure 2.6. Schematic diagram of a possible mobile underwater survey system. The cable has two fixed current electrodes and a number of potential electrodes so that measurements can be made at different spacings. The above arrangement uses the Wenner-Schlumberger type of configuration. Other configurations, such as the gradient array, can also be used.

Pseudosection buildup (profiling and sounding together and plot at 45^0 angle in opposite directions from the midpoint of C_1P_1 and C_2P_2:

Pseudosection is merely a plotting convention, and it does not imply that the depth of investigation

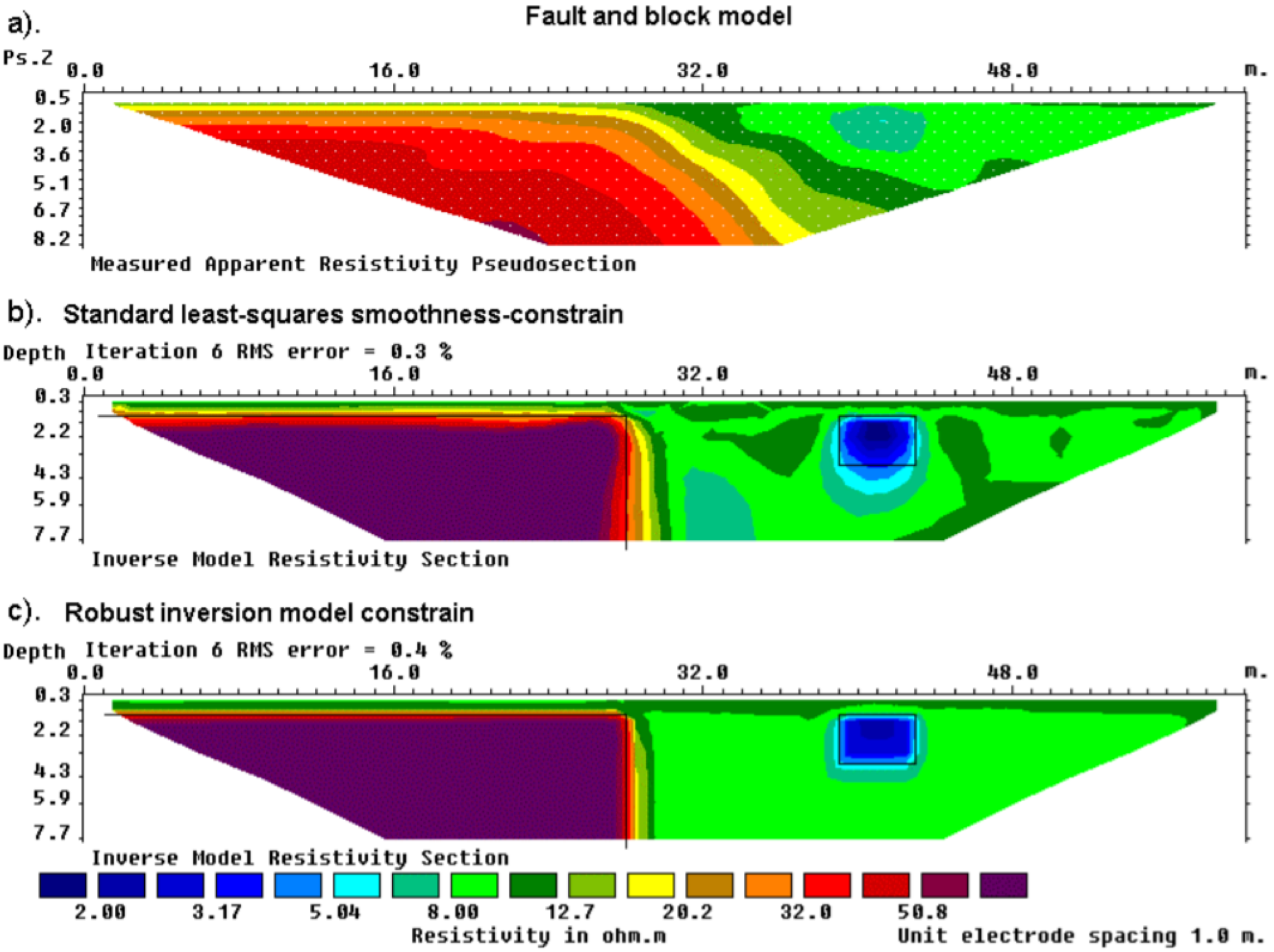


Example of inversion results using the l_2-norm smooth inversion and l_1-norm blocky inversion model constrains.

(a) Apparent resistivity pseudosection (Wenner array) for a synthetic test model with a faulted block (100 Ω·m) in the bottom-left side and a small rectangular block (2 Ω·m) on the right side with a surrounding medium of 10 Ω·m. The inversion models produced by

(b) the conventional least-squares smoothness-constrained or l_2-norm inversion method and

(c) the robust or l_1-norm inversion method.



Implementation:

- Used in search for suitable groundwater sources and also to monitor types of groundwater pollution.
- In engineering surveys to locate subsurface cavities, faults and fissures, permafrost, mine shafts.
- In archaeology for mapping out the areal extent of remnants of buried foundations of ancient buildings, amongst many other applications.
- Electrical resistivity methods are also used extensively in downhole logging.

2. EM method:

- Electromagnetic (EM) surveying methods make use of the response of the ground to the propagation of electromagnetic field. This response vary according to the conductivity of the ground (in S/m).
- Primary EM fields are generated using an alternating current in a loop wire (coil) or a natural EM source
- The response of the ground is the generation of a secondary EM field
- The resultant field is detected by the alternating currents that they induce in a receiver coil

Maxwell's Equations:

$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0 \qquad \text{Faraday induction}$$

$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{j} \qquad \text{Ampère} - \text{Maxwell}$$

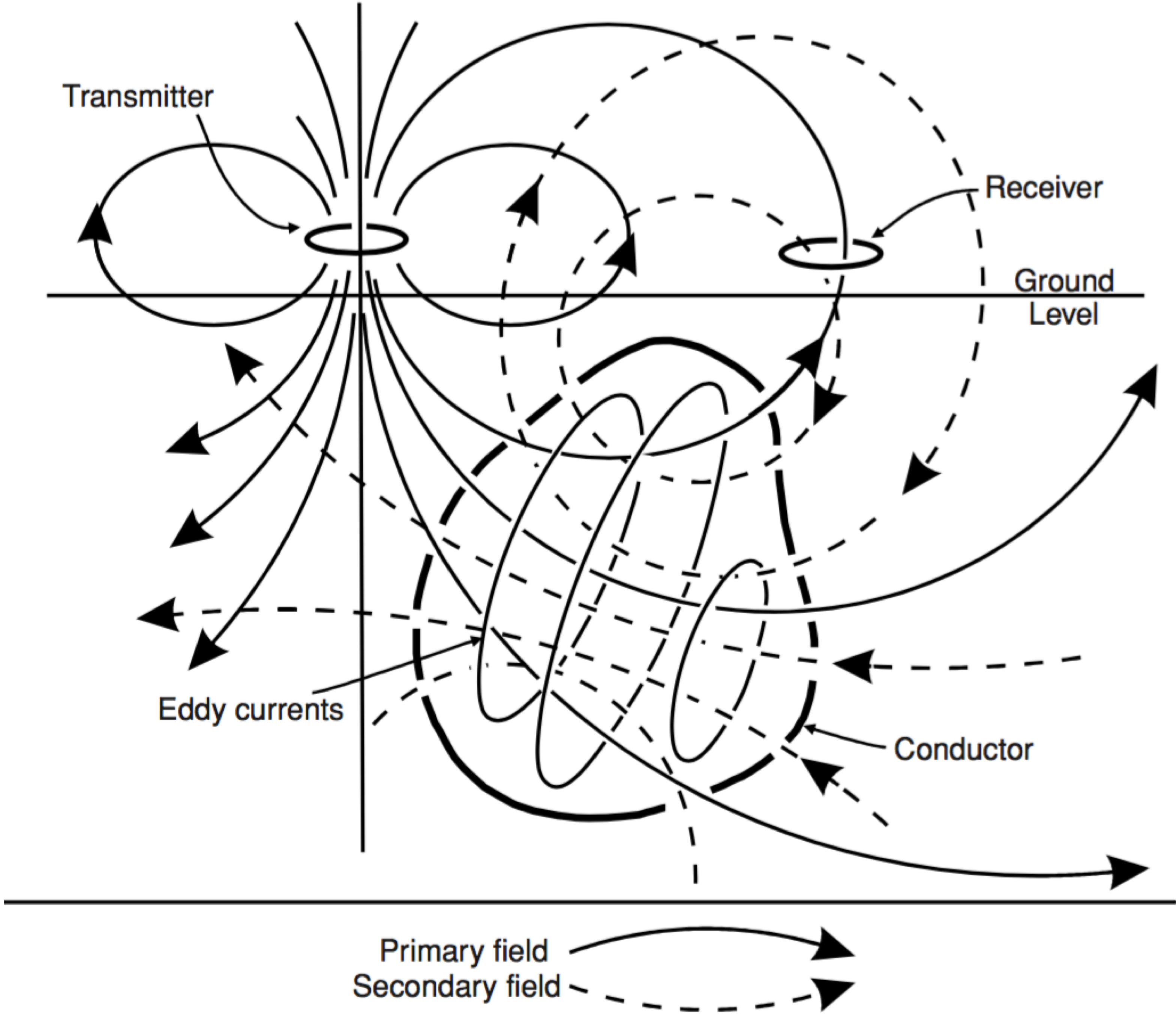
$$\nabla \cdot \vec{D} = p \quad \text{or} \quad \nabla \cdot \vec{j} = \frac{\partial p}{\partial t}$$

$$\nabla \cdot \vec{B} = 0$$

$\vec{E}$	electrical field	(V/m)
$\vec{B}$	magnetic induction field	(Vs/m^2)
$\vec{H}$	magnetic field strenght	(A/m)
$\vec{D}$	displacement field	(C/m^2)
$\vec{j}$	current density	(A/m^2)
p	charge density	(C/m^3)

EM survey

In EM exploration, a primary magnetic field is applied (*P*) which, in accordance with the properties of an EM wave, is in phase with its orthogonal electric component (***E***). The voltage induced into a secondary perfect conductor as a result of the incident primary magnetic field lags behind the primary field by π/2. According to Faraday's Law of EM induction, the magnitude of the induced voltage is directly proportional to the rate of change of the magnetic field.



TEM

(A)

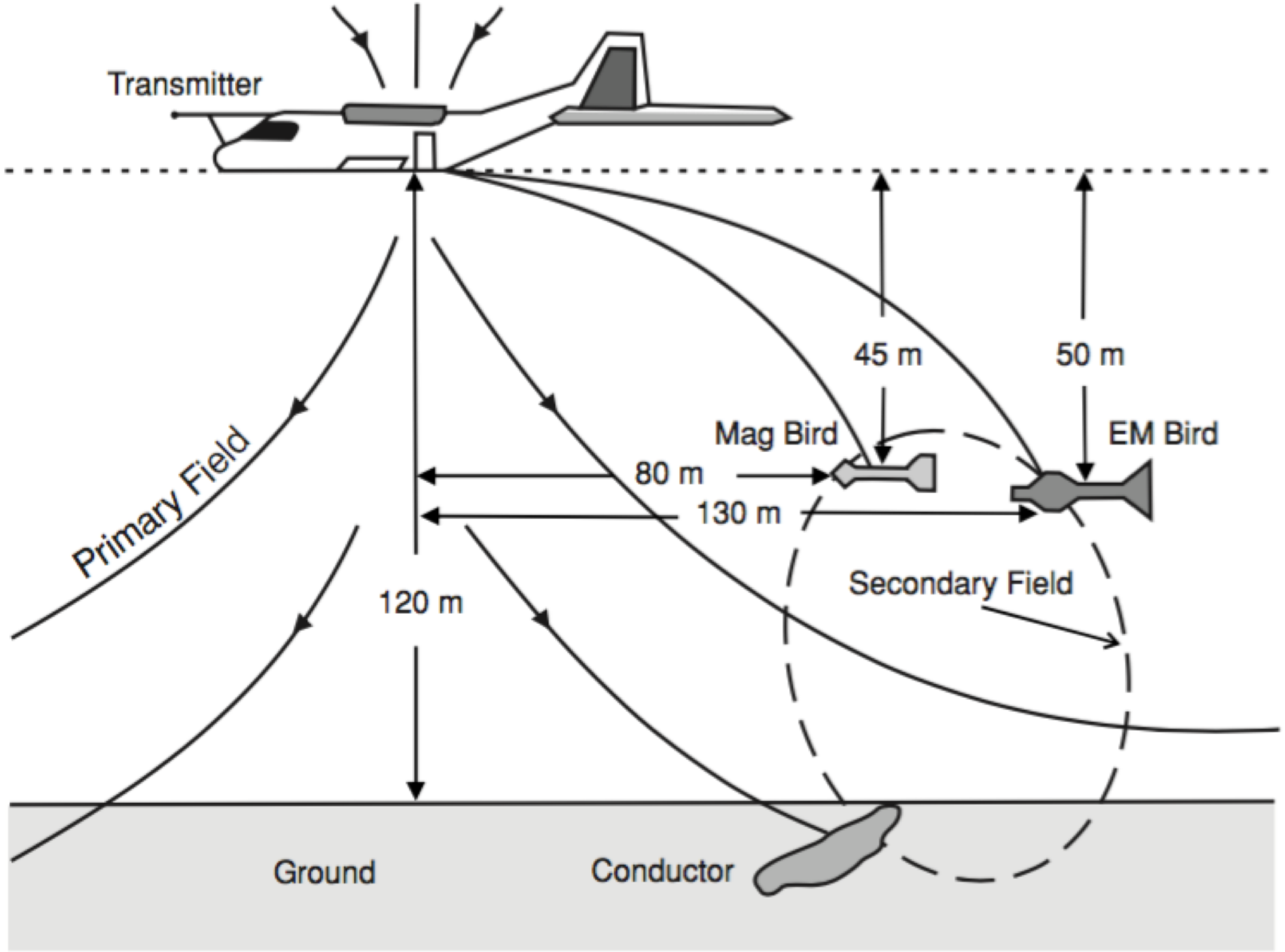
Magtem

(B)

Geotem

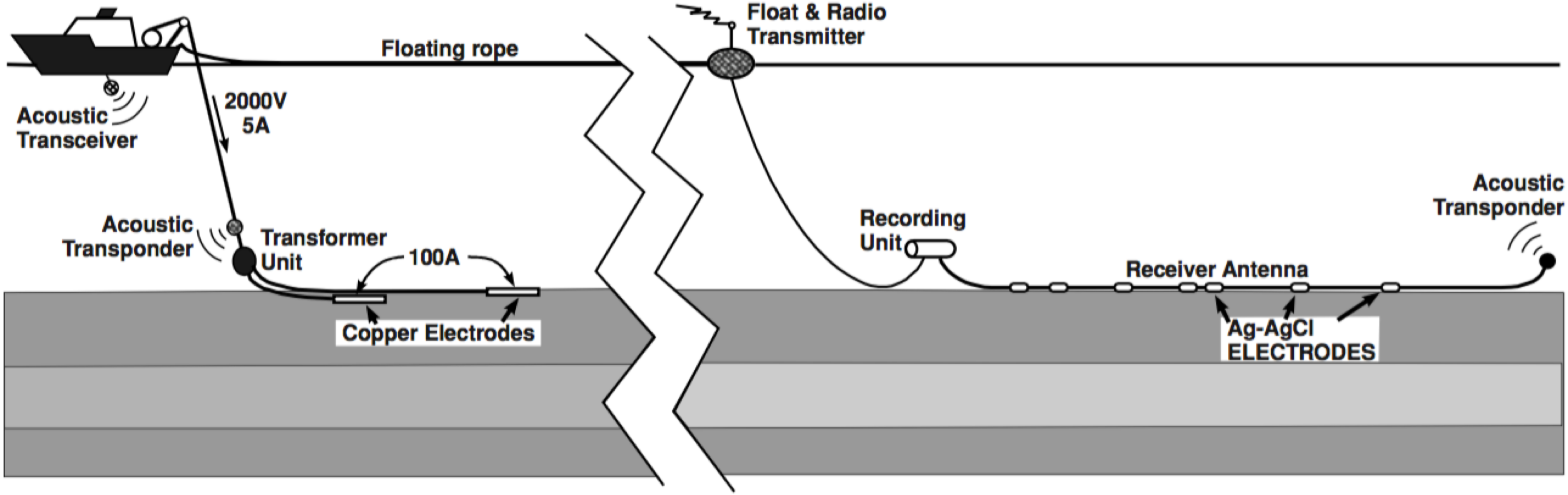
(C)

Tempest



Schematic diagram of the MEGATEM/GEOTEM system configuration. From Fountain *et al.* (2005)

Shipborne EM (CSEM)



Schematic to illustrate the components of a towed frequency-domain profiling system. The source antenna is towed immediately behind a research ship and is powered by the ship's generators. The receiving antenna is towed further behind from a radio-equipped buoy and consists of an array of Ag-AgCl electrodes. Acoustic transponders are used for location purposes. From Chave *et al.* (1991)

Applications:

- Mineral exploration
  Hydrocarbon exploration
  Monitoring hydrocarbon reservoirs Groundwater surveys
  Mapping contaminant plumes Geothermal resource
  Detection of natural and artificial cavities
- Location of geological faults
  Permafrost mapping
  Sea-ice thickness mapping Archaeological investigations

Advantages:

Surveys are easy to carry out, non-expensive (require less field operators than resistivity methods)

- Rapid qualitative overview
- No galvanic coupling with the ground required

Disadvantages:

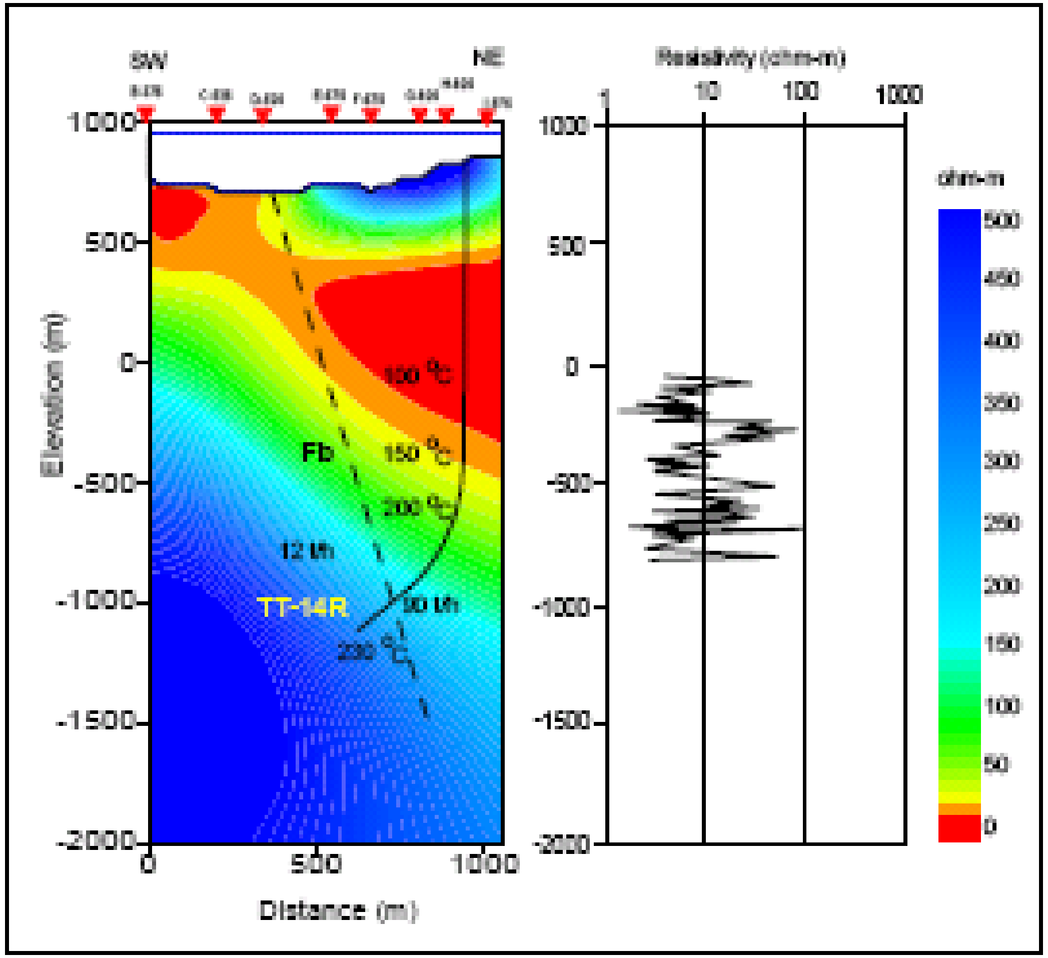
- Quantitative interpretation of EM anomalies is complex
- Penetration not very great if very conductive superficial layers are present

3. Magnetotelluric (MT) method : MT principle

- The magnetotelluric method uses time variations of Earth's magnetic field caused at low frequencies (10 Hz) by the interaction of the solar plasma with the ionosphere and magnetosphere as a source, and at high frequencies (>10 Hz) by global lightning activity.
- The fluctuating magnetic field induces an electric current within Earth whose magnitude depends on electrical conductivity, and from Ampere's law, measurements of magnetic field fluctuations at Earth's surface determine the total electric current in the subsurface.
- The addition of an electric field measurement at Earth's surface yields the electrical conductivity at that point, and transformation of electric and magnetic field data into the frequency domain allows the geophysicist to map the electrical conductivity as a function of depth and position (and occasionally, with time, in continuous or repeat four dimensional experiments).
- Since the electromagnetic fields are vector entities, it is possible to measure three components of the magnetic field and the two horizontal components of the electric field at Earth's surface, where the vertical electric field vanishes due to the presence of the insulating atmosphere.
- MT is one of the few techniques capable of sensing through the Earth's crust to upper mantle.

Fracture/fault detection: MT examples

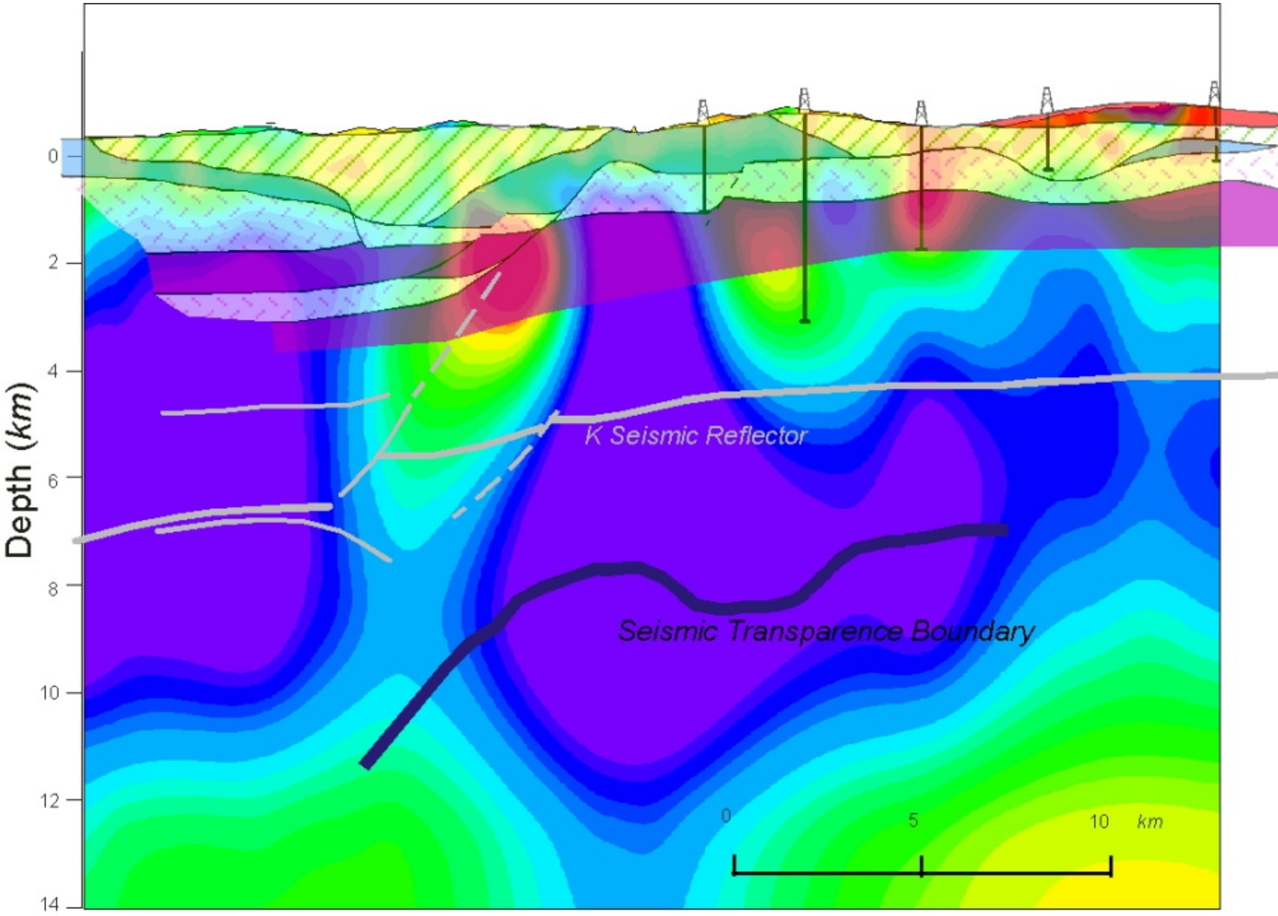
Takigami Gothermal Area, Japan



From Tagomori et al., WGC 2005

"the large lost circulation occurred at the depth of 1300 m BSL for the well TT-14R (90 t/h) when the well crossed through the electrical discontinuity Fb"

Mt. Amiata Geothermal Area, Italy



From Fiordelisi et al., WGC 2000

Note the very steep conductor and its correspondence in location to the fault defined by seismic reflection data.

4. Ground Penetrating Radar (GPR)

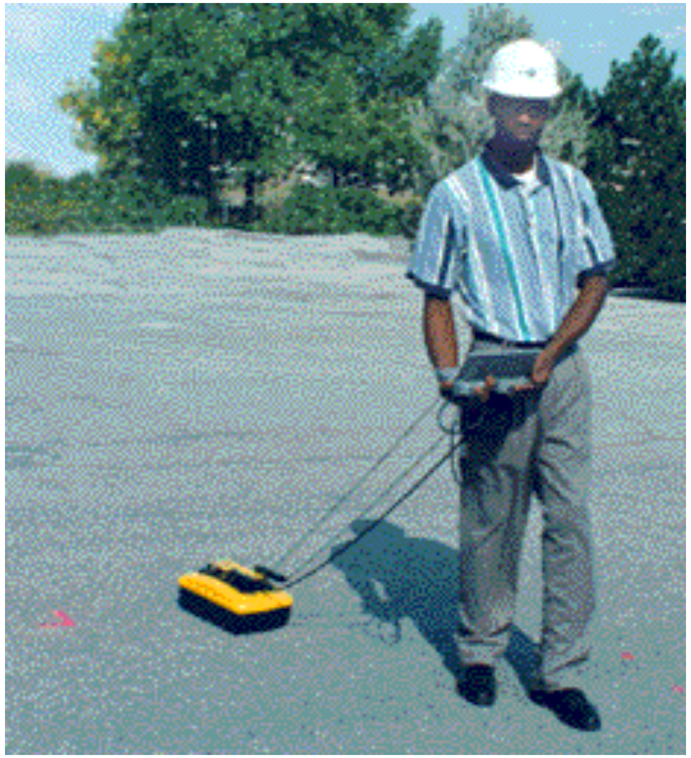
GPR is a technique of imaging the very near-subsurface (up to 30 m in dry sands; only 3 m in wet saturated clay) at high resolution.

Since the mid 1980s, GPR has become enormously popular, particular with the engineering and archaeological communities.

It was applied since the 1960s in connection with the development of radio-echosounding of polar ice sheets. For regional and largescale investigations, radar measurements have been made from aircraft and satellites.

➔ Ancient river drainage systems now buried beneath desert sands in Africa
➔ important source of possible water

Ground Penetrating Radar (GPR)



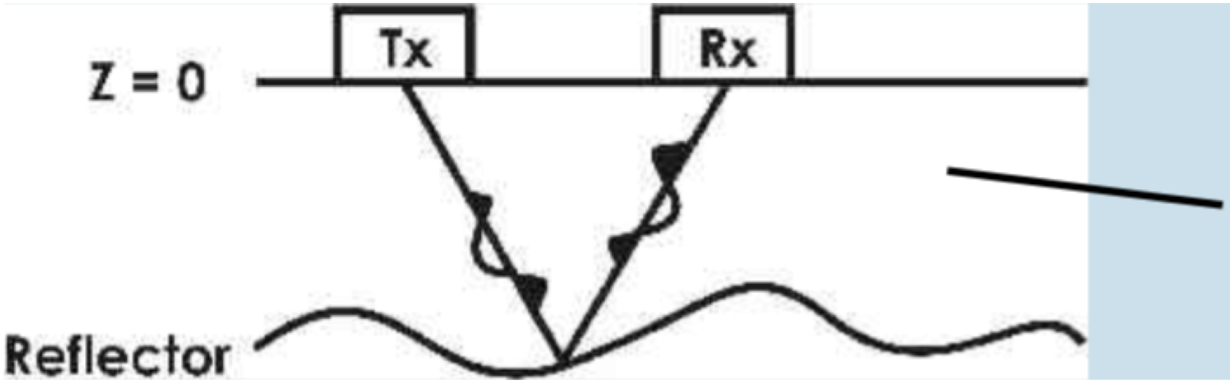
Xadar

Sensors & Software

GeoRadar

GPR principle

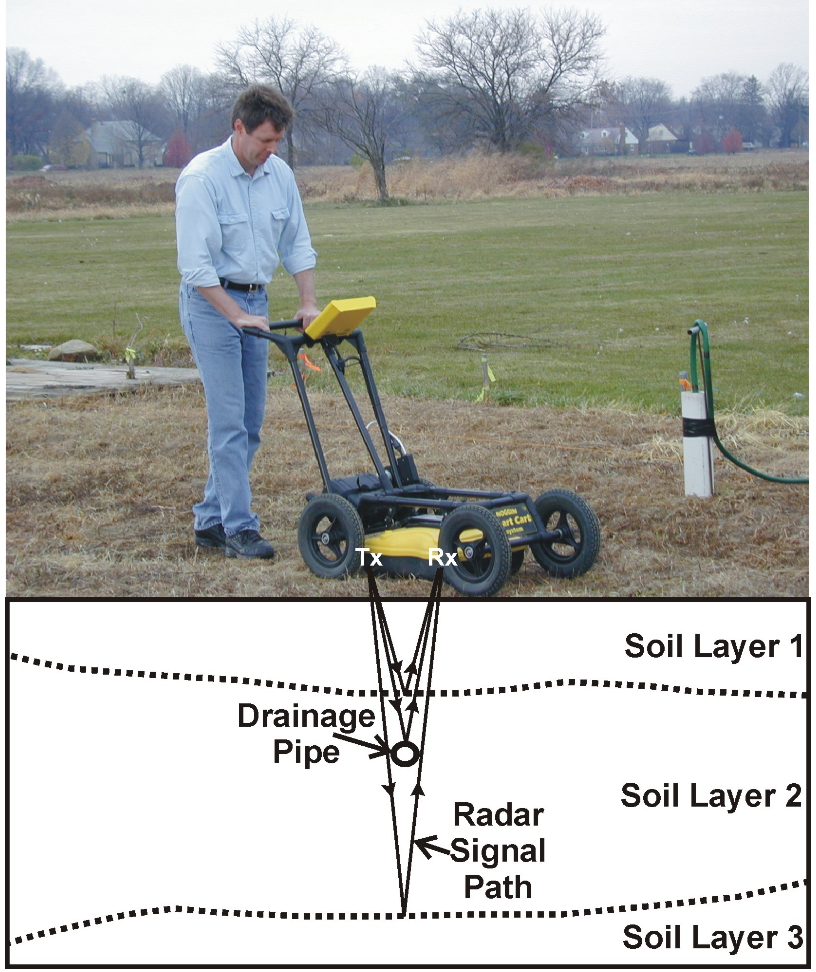
In the GPR method, a short radar pulse in the frequency band 10MHz -1GHz is introduced in the ground. The reflection of electromagnetic waves are observed.



$$V = \frac{c}{\sqrt{\epsilon_r \cdot \mu_r}}$$

Radar velocities are controlled by the dielectric constant ϵ_r where c is the velocity of light in vacuum ($3 \cdot 10^8$ m/s), and μ_r is the relative magnetic permeability which is close to unity for nonmagnetic rocks.

material	ϵ_r	σ (ms/m)	v (m/ns)	α (dB/m)
water	80	0.5	33	0.1
dry sand	3 – 5	0.01	0.15	0.01 – 1
wet sand	20 – 30	0.1 – 1	0.06	0.03 – 0.3
clay	5 – 40	2 – 1000	0.06	1 – 300
granite	6	0.01 – 1	0.12	0.01 – 1



A radar system comprises a signal generator, transmitting and receiving antennae and a receiver that may have recording facilities.

● As radiowaves travel at high speeds (in air 300 000 km/s), the travel time is a few tens to several thousand nanoseconds (ns=10^{9}s). This requires a very accurate instrumentation to measure the signal.

● The antennae used can be in monostatic or bistatic mode.

monostatic: one antenna device is used as both transmitter and receiver

bistatic: two seperate anntennae are used with one serving as transmitter and the other as receiver

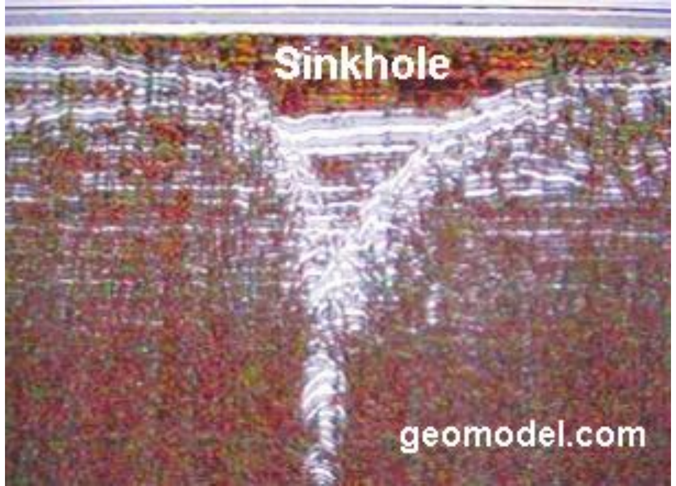
What's the wavelength of the signal at 100 MHz?

Velocity = distance / time

Wavelength = distance / cycle

Frequency = cycles / time

Wavelength = velocity / frequency = $3*10^{8}$ m/sec / 10^{8} cycles/sec = 3 meters



Implications of GPR

- contaminant plume mapping
- landfill investigations
- location of buried fuel tanks and oil drums
- detection of natural cavities and fissures
- void detection
- ice thickness mapping
- location of buried archaeological objects