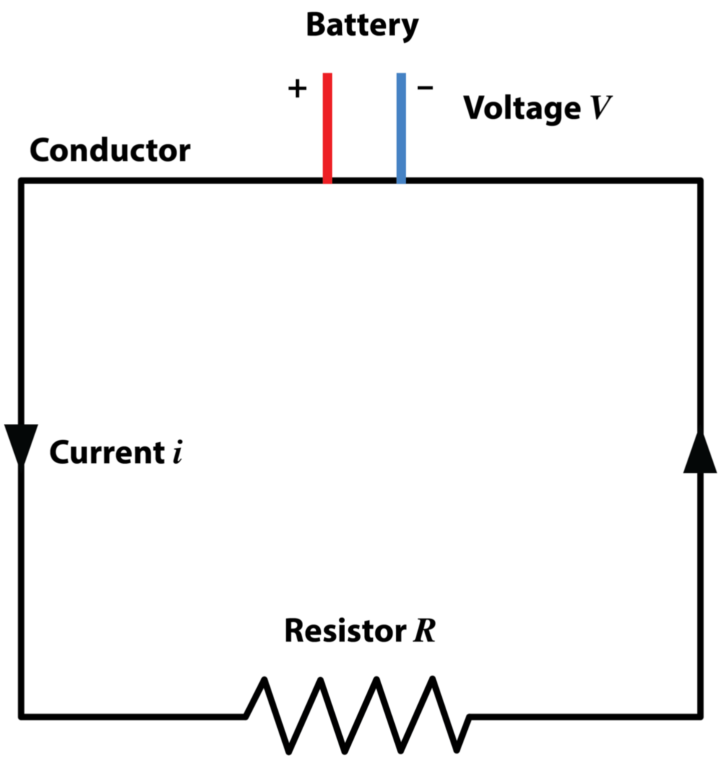
Electrical Resistivity Methods

Basic electricity – Ohm's law

- Current *i* (Amps): movement of charges across a cross-sectional area in a unit of time
- *R* is the electrical resistance of an object and measures its opposition to the passage of an electric current, in ohms (Ω)
- More *V* (Volt) required if high resistance to maintain same *i*



Geoelectric – electrical resistivity

Electrical resistivity in explorational geophysics works by injecting an electrical current into the ground through electrodes and measuring the resulting voltage differences.

The resistance of the subsurface materials to this current flow is then calculated, which varies depending on factors such as soil composition, water content, and rock type.

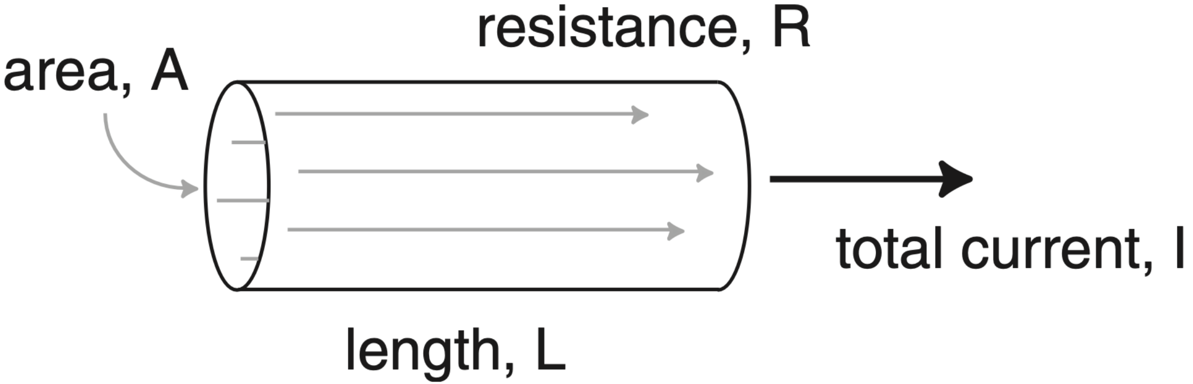
By analyzing these resistivity measurements, we can create models of the subsurface structure, helping to identify geological features, groundwater resources, or potential mineral deposits.

Basic electricity – Ohm's law

$$R \propto \frac{l}{A}$$

$$R = \rho \frac{l}{A}$$

$$\rho = \frac{RA}{L} \; [\Omega m]$$



Concept of "resistivity"

Resistivity (ρ) measures how strongly a material opposes the flow of electric current.

Unit: Ohm-meters (Ωm)

<u>Higher resistivity means the material is less conductive.</u>

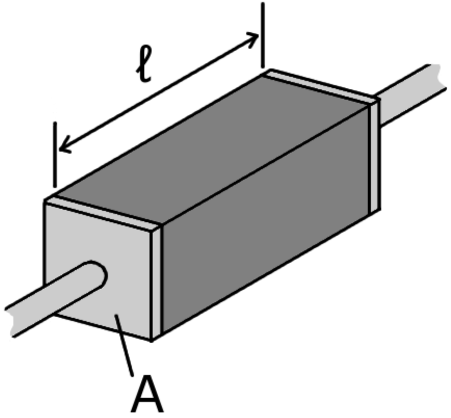
$$\rho = \frac{R\ A}{l}$$

ρ (rho) is the resistivity in ohm-meters (Ω·m)

R is the electrical resistance of the material in ohms (Ω)

A is the cross-sectional area of the material in square meters (m^2)

l is the length of the material in meters (m)



Concept of "conductivity"

Conductivity (σ): the inverse of resistivity. Measures how easily a material allows electric current to flow. Higher conductivity means the material is more conductive.

Siemens (S) is a unit of electric conductance (1/resistance, Ω^{-1}, or Mho)
We also use mS/m since rocks have low conductivity

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

Resistivity

Geomaterial	Resistivity [Ωm]
Clay	1–20
Sand, wet to moist	20–200
Shale	1–500
Porous limestone	$100–10^3$
Dense limestone	$10^3–10^6$
Metamorphic rocks	$50–10^6$
Igneous rocks	$10^2–10^6$

High resistivity R

Igneous rocks
Why? Minor component of water

Metamorphic rocks
Why? Hydrous mineral and fabrics

Sedimentary rocks
Why? Abundant pore space and fluids

Low resistivity R

High resistivity R

Older rocks
Why? More time to fill fracture and pore space

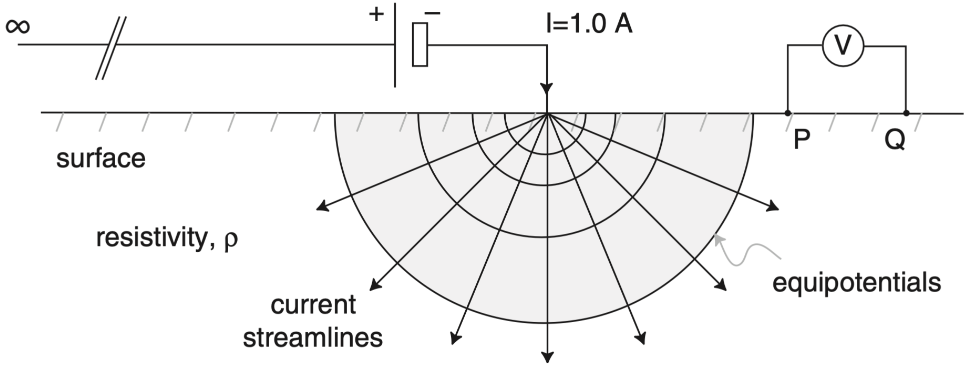
Younger rocks
Why? Abundant pore space and fractures

Low resistivity R

Current flow

A direct current of 1.0 A is injected into the ground through a pair of electrodes. The positive (+) and negative (−) terminals indicate the direction of current flow to the electrode.

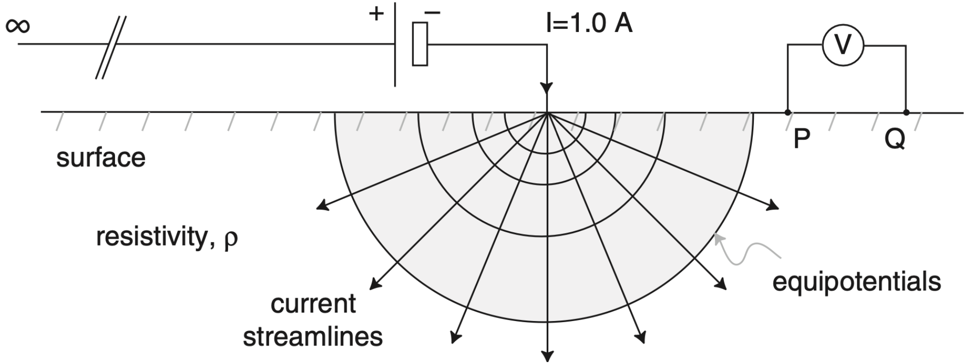
The arrows radiating outward from the injection point represent current streamlines, (the flow of electrical current). These streamlines distribute radially because the current spreads as it moves away from the electrode.



Current flow

The concentric semicircles represent equipotential lines, which are points in the subsurface with the same electrical potential (electric field and potential gradient are orthogonal).

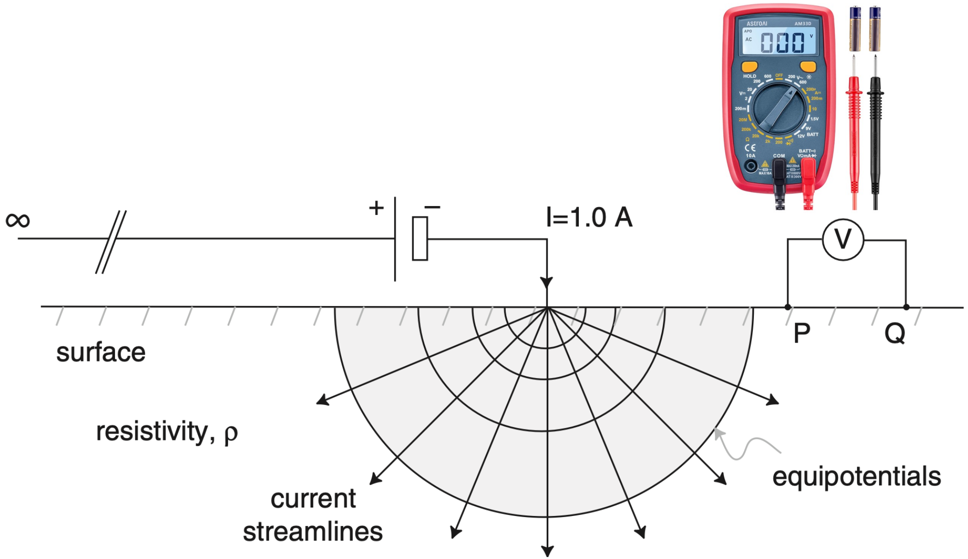
The figure highlights the importance of resistivity (ρ), a property of the subsurface material that affects current flow.



Current flow

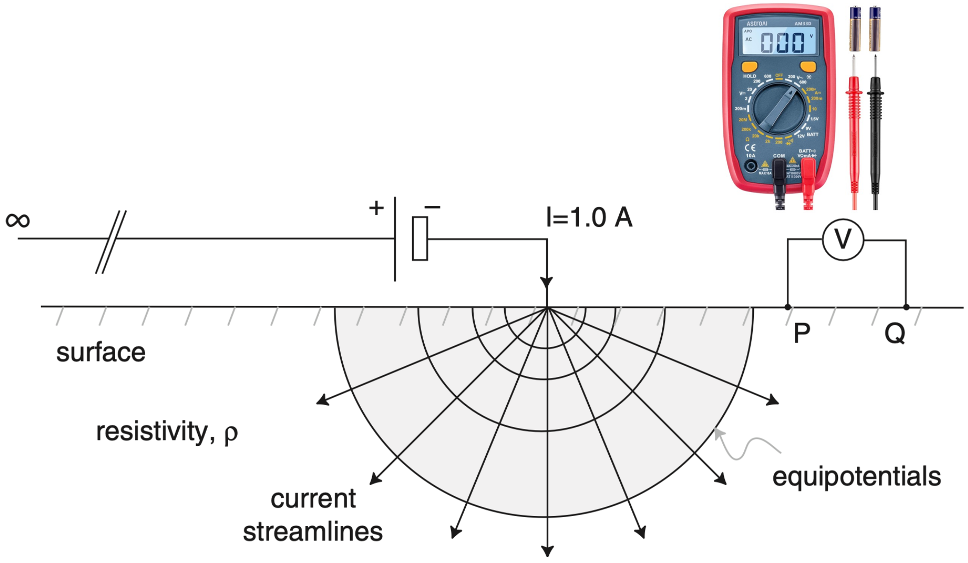
The points P and Q on the surface indicate where potential differences are measured using a voltmeter (V). This potential difference, combined with the known current, can be used to calculate resistivity using Ohm's Law:

$$R = \rho \frac{l}{A}$$



Steps to calculate resistivity

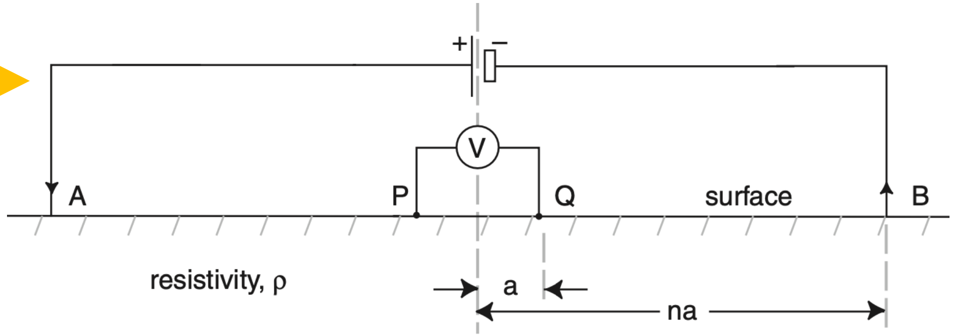
Measure the potential difference (V) between points P and Q.
Inject a known current (I) through the current electrodes.
Calculate the geometric factor (k) based on the electrode arrangement.
Use the formula $\rho_a = k\,(V/I)$ to determine the apparent resistivity.



Geometrical factor & electrode configurations

$$\kappa = (n-1)(n+1)\pi a/2$$

Schlumberger



Advantages:

Greater depth penetration with fewer electrode movements.

Efficient for large-scale surveys.

Good vertical resolution for detecting layer boundaries.

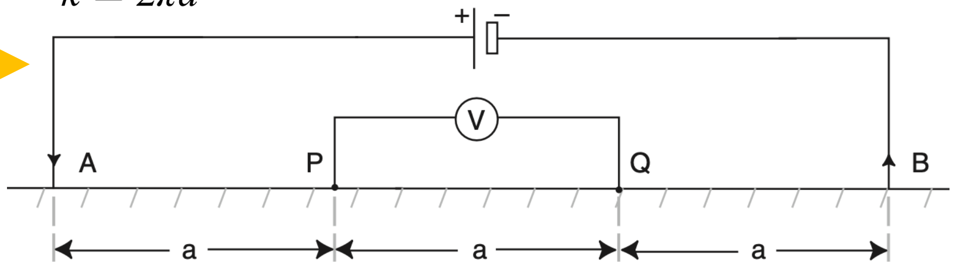
Disadvantages:

Lower signal strength compared to Wenner, making it sensitive to noise.

More complex data processing.

Geometrical factor & electrode configurations

$$\kappa = 2\pi a$$



Wenner

Advantages:

- High signal strength, good for noisy environments.
- Simple setup and calculation.
- Good horizontal resolution for detecting lateral changes.

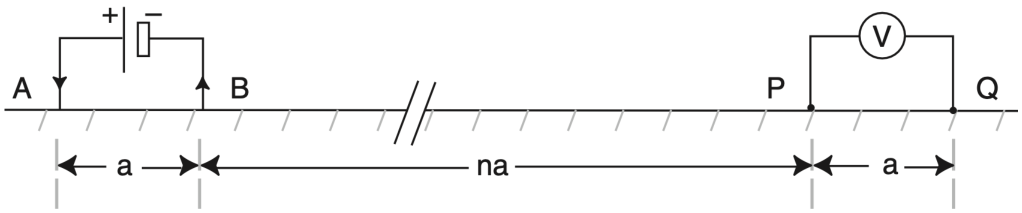
Disadvantages:

- Requires frequent electrode movement for deeper investigations.
- Limited depth penetration compared to Schlumberger.

Geometrical factor & electrode configurations

Dipole-dipole

$$\kappa = \pi n(n+1)(n+2)a$$



Advantages:

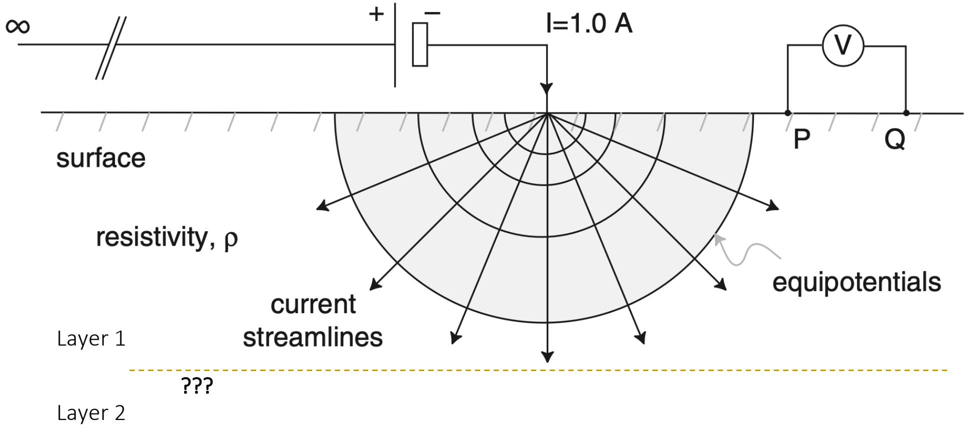
High sensitivity to lateral changes, ideal for mapping faults or fractures.
Good for detailed 2D and 3D subsurface imaging.

Disadvantages:

Weak signal strength, more susceptible to noise.
Requires precise electrode spacing and more complex data interpretation.

Current flow lines: Multi-layer models

The above discussion outlined the formulas necessary to compute voltages that would be recorded over a homogeneous Earth. In the case of multiple layers of uniform resistivity, the calculations are more involved.



Current flow lines: Multi-layer models

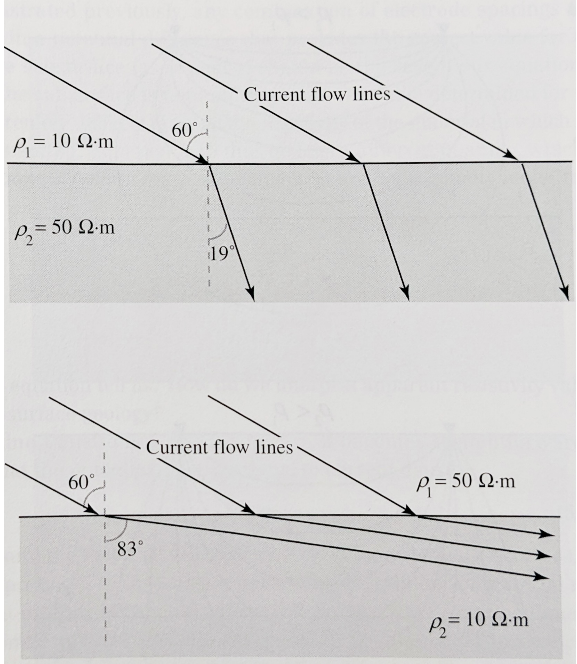
$$\frac{\tan\theta_1}{\tan\theta_2} = \frac{\rho_2}{\rho_1} = \frac{\sigma_1}{\sigma_2}$$

Ohm's Law states that the current density (J) is proportional to the electric field (E) and the material's conductivity (σ):

$$J = \sigma E$$

$$J = I / A \text{ (unit: Ampere / meter}^2\text{)}$$

When electric current encounters a boundary between two materials with different conductivities or resistivities ($\rho = 1/\sigma$), the electric field adjusts to maintain continuity of the current flow. This adjustment results in the bending of current flow lines at the interface.



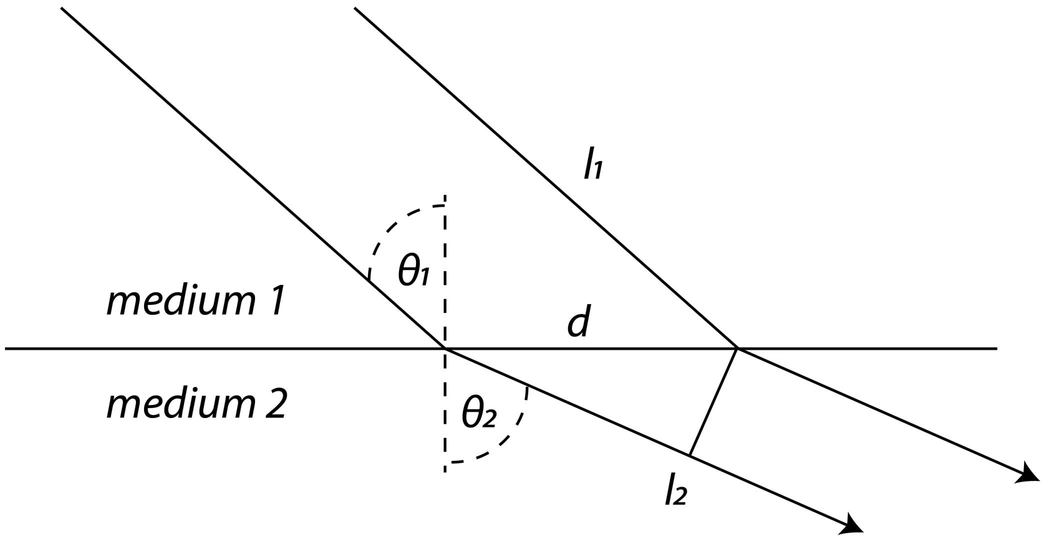
Analogy to refraction: Like light bending between media with different refractive indices (Snell's Law), electric current lines bend at interfaces between materials with different resistivities, with the bending depending on the resistivity contrast.

Current flow lines: Multi-layer models

$$\Delta t = \frac{l_1}{v_1} = \frac{l_2}{v_2}$$

This equation implies that the time required for the current to travel a given path length l in either medium is inversely proportional to the velocity v of the current in that medium.

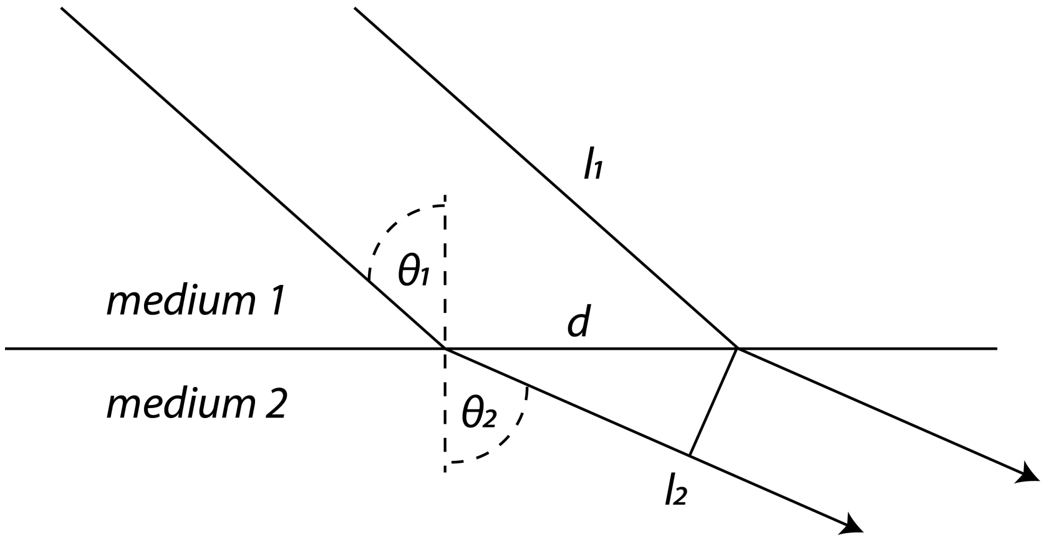
It suggests that the total travel time remains constant across the interface between layers.



Current flow lines: Multi-layer models

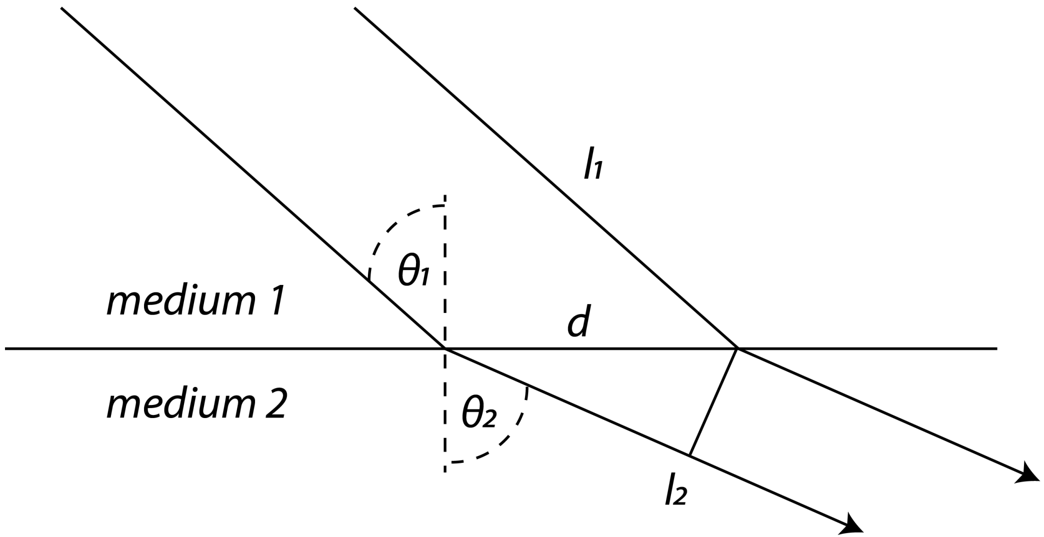
$$\frac{d \sin \theta_1}{v_1} = \frac{d \sin \theta_2}{v_2}$$

This equation ensures that the current lines bend consistently when transitioning between layers of different velocities (related to resistivity).



Current flow lines: Multi-layer models

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$$



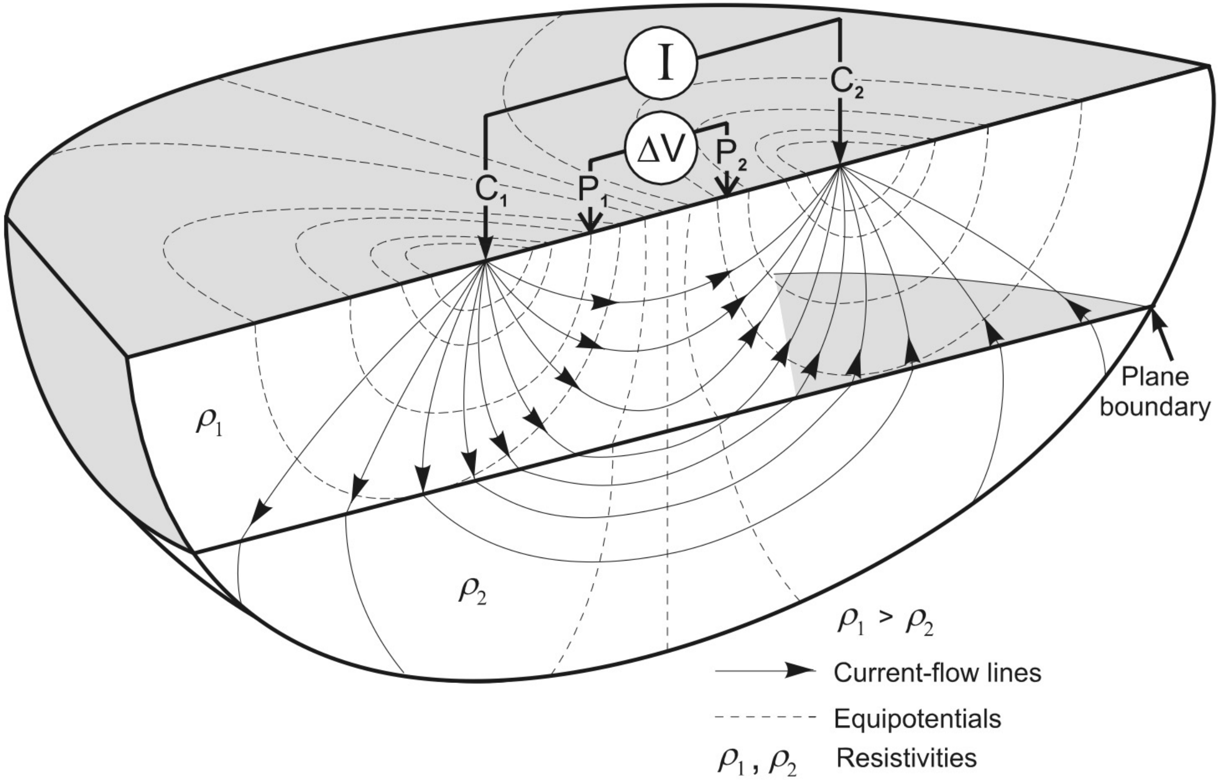
This is an adaptation of Snell's Law:

θ_1 and θ_2 are the angles of the current lines relative to the normal in medium 1 and medium 2, respectively.

n_1 and n_2 represent the refractive indices (or resistivity-related factors) of the two layers.

The ratio v_1/v_2 reflects the contrast in current velocities between the two media.

Current flow lines: Multi-layer models



Modes of operation

- Profiling (mapping).
- Vertical electrical sounding (VES).
- Combined sounding and profiling (2-D resistivity imaging).
- Electrical resistivity tomography (ERT).

Profiling (mapping)

- Purpose and Application: Provides information on lateral resistivity distribution within a defined depth range. Commonly used in environmental surveys to identify concealed waste dumps or contamination plumes.

- Methodology: Fixed electrode arrays (e.g., Wenner, Schlumberger, dipole-dipole) are moved along profiles or a grid. Depth of investigation varies slightly with subsurface resistivity changes.

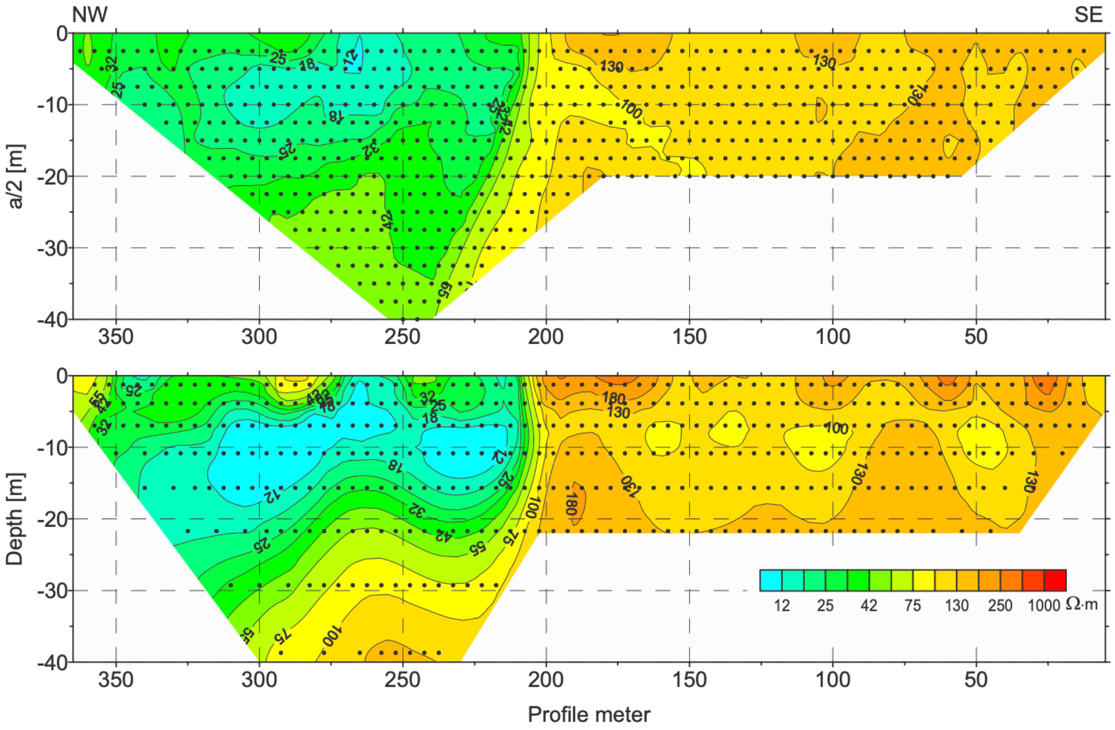
- Advantages and Limitations: Optimized depth resolution by using results from vertical electrical soundings at key points. Disadvantages include high personnel requirements (3-4 people) and the need to move long cables.

Profiling (mapping)

Resistivity survey of a concealed landfill in a former quarry.

Top: Pseudo-section of apparent resistivity.

Bottom: calculated resistivity cross-section.



Vertical Electrical Sounding (VES)

- Purpose and Application: VES provides information on layer thickness and resistivity, offering insights into lithological properties and pore fluid composition. Effective for investigating horizontally layered ground and deep depths (>100 m) but increasingly supplemented by 2-D resistivity.

- Methodology: Utilizes Schlumberger array for high vertical resolution. The current electrode spacing (L) is increased stepwise (logarithmic increments recommended). Potential electrode spacing adjusted only when signal strength drops.

- Data Collection and Processing: Soundings performed on a grid or along profiles; results from one sounding aid the next. Log-log plots used in the field for quality control, enabling identification of data outliers.

2/3-D Resistivity Surveys

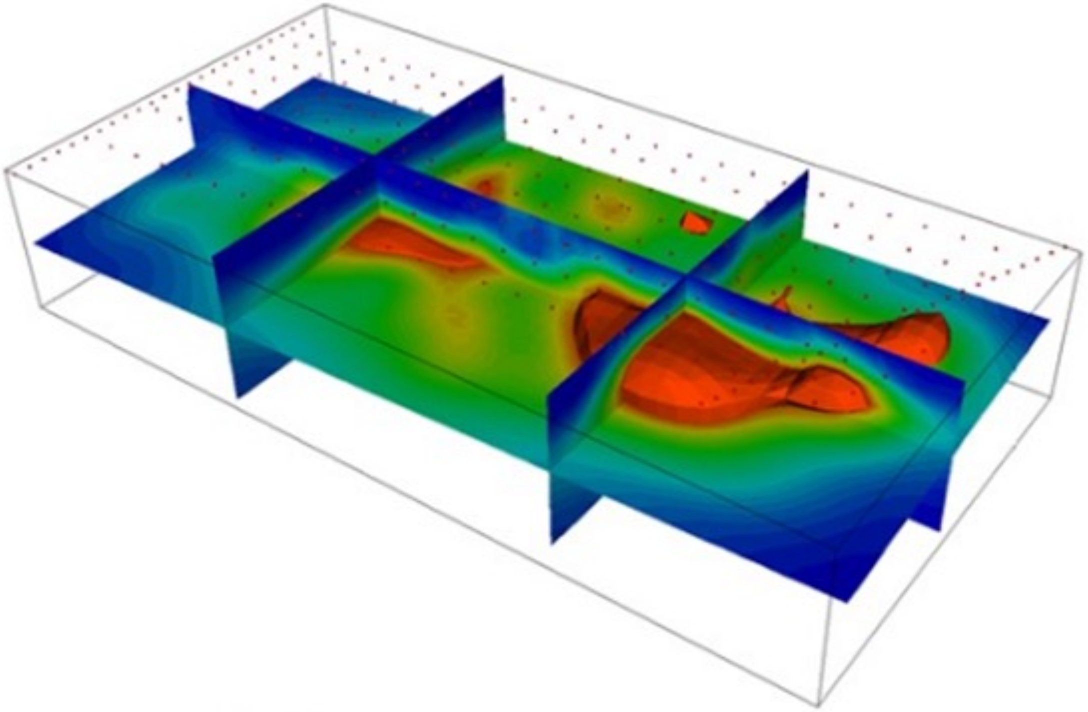
- Purpose and Benefits: High vertical and lateral resolution, ideal for 2-D/3-D environmental studies. Cost-effective with computer-driven data acquisition; small crew required (1-2 people). Effective for depths up to 100 m.

- Equipment and Setup: Uses multi-electrode systems with multi-core cables. Equal electrode spacing ensures accurate data; good ground coupling is critical.

- Measurement Process: Controlled by a resistivity meter or computer, with stepwise increased electrode spacing. Results plotted as a pseudosection (apparent resistivity vs. location and depth).

- Survey Logistics: Profiles use 2-3 cables; bends kept under 15 degrees to avoid errors.

2/3-D Resistivity Surveys



Electrical Resistivity Tomography (ERT)

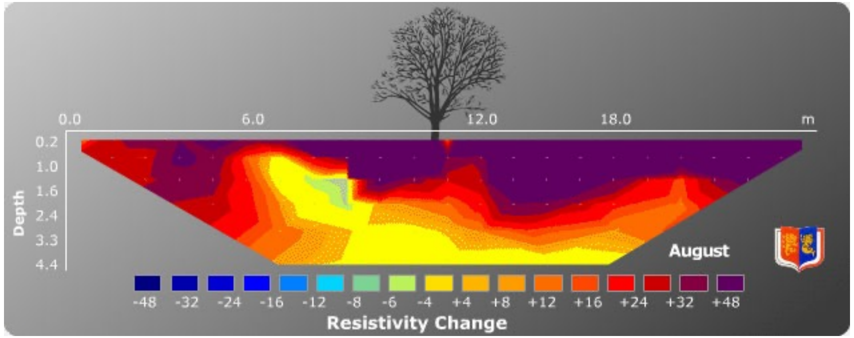
- Purpose and Application: ERT is a geophysical technique used to image subsurface structures by measuring electrical resistivity variations. It's applied in environmental studies, geotechnical engineering, archaeology, mining, and hydrogeology.

- Methodology: Involves placing multiple electrodes on the ground surface or in boreholes. A controlled current is injected through electrode pairs, and the resulting potential differences are measured. Data is processed to create a 2D or 3D resistivity model of the subsurface.

- Advantages: Non-invasive and provides high-resolution images of subsurface resistivity distributions. Effective in detecting features like groundwater, contamination plumes, voids, and archaeological artifacts.

Electrical Resistivity Tomography (ERT)

Deployment of a permanent electrical resistivity tomography (ERT)



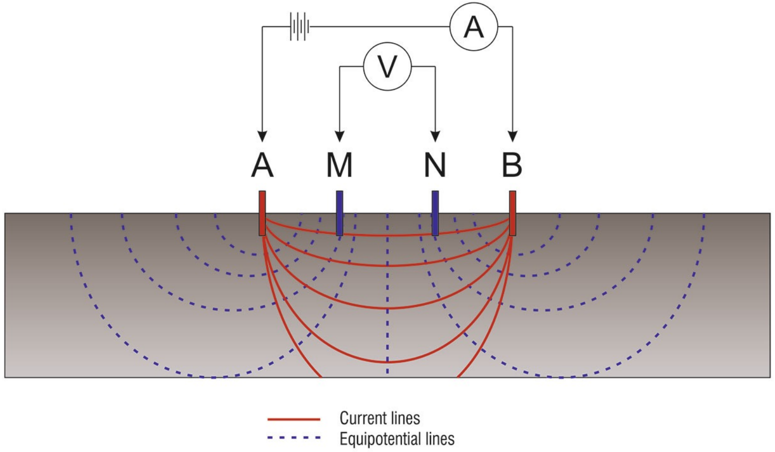
Recap: Sounding vs. Profiling

Resistivity Sounding (Vertical Electrical Sounding - VES):

- Objective: Determine how resistivity varies with depth to identify vertical changes in subsurface layers.
- Method: The electrode spacing is systematically increased while keeping the array cantered at a fixed location. This approach allows the injected current to penetrate deeper, providing information about the resistivity distribution at various depths beneath the survey point.
- Application: Ideal for identifying vertical stratification, such as detecting different soil or rock layers, groundwater tables, or bedrock depth.

Recap: Sounding vs. Profiling

Resistivity Sounding (Vertical Electrical Sounding - VES):



Recap: Sounding vs. Profiling

Resistivity Profiling (Electrical Profiling):

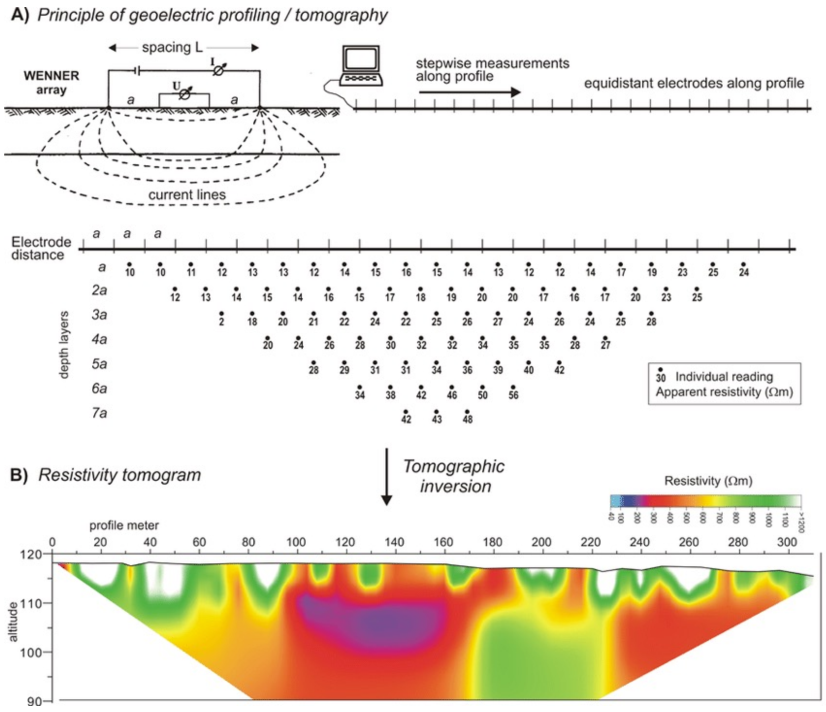
Objective: Detect lateral variations in resistivity to map horizontal changes in subsurface features.

Method: The electrode spacing remains constant, but the entire array is moved along a survey line across the area of interest. This technique highlights changes in resistivity at a consistent depth, revealing lateral discontinuities.

Application: Suited for locating horizontal structures like faults, cavities, or ore bodies, and for mapping lateral changes in lithology.

Recap: Sounding vs. Profiling

Resistivity Profiling (Electrical Profiling):



Sounding vs. Profiling

Sounding

- To estimate the conductivity structure as a function of depth in one place
- Increase the spacing between the transmitter (T) and receiver (R), while center point fixed
- Penetration depth increases with distance between T and R

Profiling

- To estimate the conductivity structure at many different places
- Cover the area of interest with fixed distance between T and R
- Most commonly used type of surveying for mapping

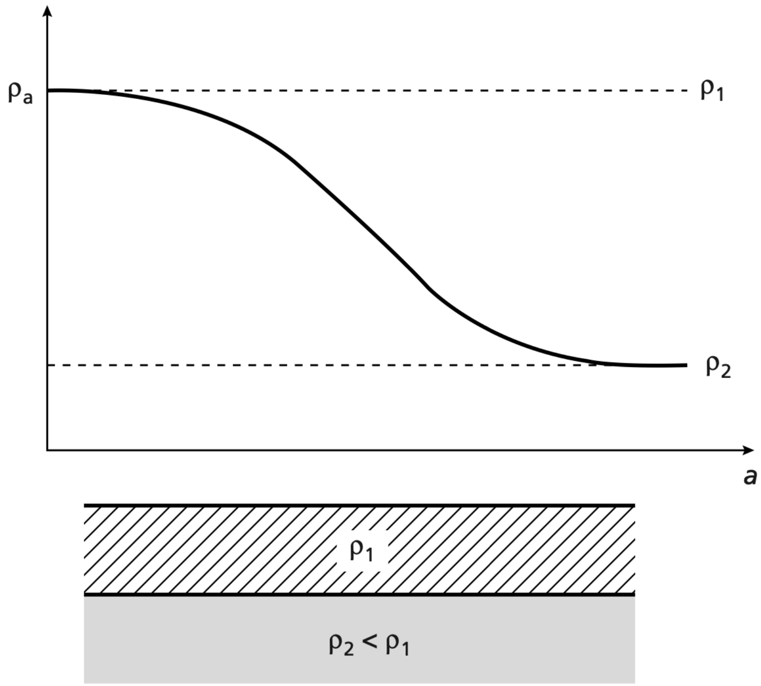
Resistivity survey: Sounding vs. Profiling

In summary, resistivity sounding focuses on vertical resistivity variations to profile subsurface layering, while resistivity profiling emphasizes lateral resistivity changes to map horizontal structures.

The choice between these methods depends on the specific geological information required for a given investigation.

Interpretation of resistivity data: example #1

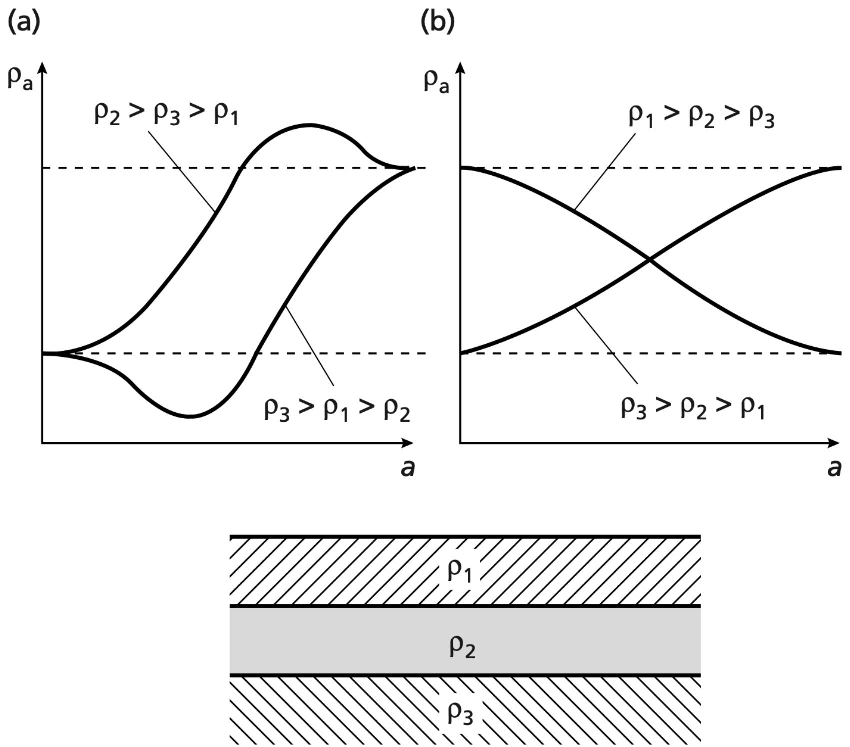
In a Wenner electrode configuration over a single horizontal interface, current flow lines bend at the interface due to the resistivity contrast between the upper layer (ρ_1) and the lower layer (ρ_2). When $\rho_1 > \rho_2$, current prefers the less resistive lower layer, causing the apparent resistivity to transition from ρ_1 (small electrode spacing) to ρ_2 (large spacing). When $\rho_2 > \rho_1$, the apparent resistivity transitions more gradually, as the more resistive lower layer is a less favourable path for the current.



The variation of apparent resistivity ρa with electrode separation "*a*" over a single horizontal interface between media with resistivities ρ1 and ρ2.

Interpretation of resistivity data: example #2

In a three-layer system, the apparent resistivity curve is more complex. For small and large electrode spacings, the apparent resistivity approaches ρ_1 (upper layer) and ρ_3 (lower layer), but the intermediate layer causes a deflection at intermediate spacings. If the intermediate layer has a resistivity higher or lower than ρ_1 and ρ_3, the curve forms a bell or basin shape. When the intermediate resistivity lies between ρ_1 and ρ_3, the curve shows a gradual increase or decrease. With four or more layers, the apparent resistivity curves become even more complex.

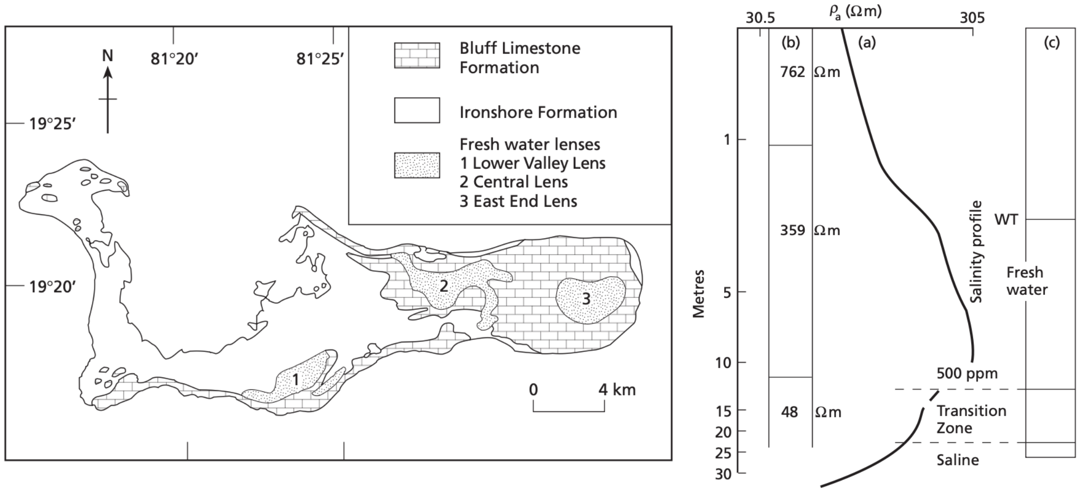


Interpretation of resistivity data: example #3

(a) Vertical electrical sounding adjacent to a test borehole in the Central Lens, Grand Cayman.

(b) Layered model interpretation of the VES.

(c) Interpreted salinity profile. (After Bugg & Lloyd 1976.)



Applications

Investigation of lithological underground structures.

Estimation of depth, thickness and properties of aquifers and aquicludes.

Detection of fractures and faults in crystalline rock.

Mapping of preferential pathways of groundwater flow.

Localization and delineation of the horizontal extent of dumped materials.

Estimation of depth and thickness of landfills.

Detection of inhomogeneities within a waste dump.

Mapping contamination plumes.

Monitoring of temporal changes in subsurface electrical properties.

Detection of underground cavities.

Classification of cohesive and non-cohesive material in dikes, levees, and dams.

Limitations

The resistivity method, as a potential field method, has inherent ambiguities, particularly in resistivity sounding, where layer thickness and resistivity are affected by the principles of equivalence and suppression.

In 1-D, the principle of equivalence implies no unique solution for layer parameters. For conductive layers, only the thickness/resistivity ratio (S-equivalence) is resolvable, while for highly resistive layers, only the product of thickness and resistivity (T-equivalence) can be determined.

Thus, variations in resistivity and thickness that maintain a constant product are indistinguishable on the sounding curve, as thickness and resistivity are inherently coupled.