Resistivity Surveying

Electrical Methods

Chapter 12
Geologic Resistivity 1101

- Resistivity surveying investigates variations of electrical resistance, by causing an electrical current to flow through the subsurface using wires (electrodes) connected to the ground.
  - Resistivity = 1 / Conductivity

But what exactly is “Resistivity?”...

A multi electrode resistivity survey

A close-up of an electrode
Resistance, Voltage, & Current

• An analogy…
  – To get water to circulate through the system below...
    • Must provide a push

• Electricity is acts in a similar way...
  – To get current to flow you must provide a push...
    • The “push” is called a potential difference or voltage
      – Symbol: p.d. V or ΔV (V [=] volts)
    • The “flow” is called the current
      – Symbol: I (I = amperes / amps)
Resistance, Voltage, & Current

• The amount of potential difference required to push a given current is directly proportional to the “Resistance”

• Ohm’s Law: \[ R = \frac{V}{I} \]
  
  – Resistance [=] Ohms (symbol = \( \Omega \))
  – But this chapter is about resistivity, not resistance...
  – Resistance, \( R \neq \) Resistivity, \( \rho \) (rho)
    • They are related, but are fundamentally different things...

How do we measure resistance? Why does this work?

[Diagram of electrical circuit with ammeter, voltmeter, and resistance. Graph showing slope equal to resistance.]
Resistivity...Finally

- **Resistance depends on:**
  - The material properties
    - i.e. the resistivity, $\rho$ (so, yes, $\rho$ is a material property!)
  - The shape of the material that has current flowing through it.

$$ R = \rho \frac{l}{a} \quad \text{Or...} \quad \rho = R \frac{a}{l} $$

- **$R$ = Resistance, $a =$ cross sectional area, $l =$ length**

- **Therefore...**
  - Resistance is higher when current is forced through a:
    - Small area
    - Long length
Resistivity...How Do We Measure It?

• So, now, you can probably figure out how we measure the resistivity of a material
  – Apply a known potential difference (measured with voltmeter) to a circuit with a resistive material of known length and cross-sectional area.
  – Then measure the current (with ammeter)
  – This gives the resistance, $R$
    • Use the length and cross sectional area to calculate $\rho$

But wait! Doesn’t adding these devices to the circuit change the overall resistance?
Resistors in Series

- A “series” circuit has more than one resistor in series (one after the other)
  - Series: all current must travel the same path
- Two or more resistors in series behave like one resistor with an equivalent resistance, $R_{eq}$ of...

$$R_{eq} = R_1 + R_2$$

Or in general...

$$R_{eq} = \sum_{i=1}^{n} R_n$$

This rule does not apply to all electrical devices. E.g., capacitors are different.
Resistors in Parallel

- Parallel circuit: The current can take multiple paths
- A “parallel” circuit has more than one resistor in parallel (the current is split among the Rs)

\[
R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} \quad \text{Or in general...} \quad R_{eq} = \left( \sum_{i=1}^{n} \frac{1}{R_n} \right)^{-1}
\]
Measuring Resistivity

- **Voltage is measured by a voltmeter**
  - Plugged in parallel with the R of interest
  - Hi R value

- **Current is measured by an ammeter**
  - Plugged in series along the branch of the circuit shared by the R of interest
  - Low R value

\[
R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = R_1 \quad (R_2 \approx \infty)
\]

\[
R_{eq} = R_1 + \left(R_2 \approx 0\right) = R_1
\]

So, the ammeter and voltmeter do not have an effect on the circuit’s resistance
Resistivity of Geologic Materials

- The resistivity of the subsurface depends upon:
  - The presence of certain metallic ores
    - Especially metallic ores
  - The temperature of the subsurface
    - Geothermal energy!
  - The presence of archeological features
    - Graves, fire pits, post holes, etc...
  - Amount of groundwater present
    - Amount of dissolved salts
    - Presence of contaminants
    - % Porosity and Permeability
Atomic Charge?

• Recall that matter is conceptualized as being made of atoms:
  – + charged nucleus (protons + neutrons)
  – - charged electrons circle the nucleus in a cloud pattern
  – Usually these charges are balanced
    • E.g. H₂O, NaCl, KAl₂Si₂O₈, (Mg,Fe)₂SiO₄
  – An imbalance in charge (i.e. ions), gives a body a net charge.
    • SO₄²⁻, O²⁻
  – Resistivity is concerned with the FLOW of charge, not the net charge or any imbalance in charges
Types of Conduction

• Conduction refers to the flow of electricity (or other types of energy)
  – For electric conduction: Three basic flavors

• Electrolytic / Ionic
  – Slow movement of ions in fluid

• Electronic
  – Metals allow electrons to flow freely

• Di-electric
  – Electrons shift slightly during induction
    • We won’t cover this
Conduction in the Earth

- In rocks, two basic types of conduction occur
  - Electronic: Electrons are mobile in metallic ores and flow freely
    - Metals (wires) and some ore bodies
  - Electrolytic / Ionic: Salts disassociate into ions in solution and move
    - Involves motion of cations (+) and anions (-) in opposite directions

(a) rock

(b) metal or conducting ore
Archie’s Law

- Porous, water-bearing rocks / sediments may be ionic conductors. Their “formation resistivity” is defined by Archie’s Law:
  \[ \rho_t = a \rho_w \phi^{-m} s_w^{-n} \]

- Archie’s law is an empirical model
  - Note the exponents...what does this imply about the range of resistivity of geologic materials?

  \( \phi \equiv \) porosity
  \( s_w \equiv \) water saturation
  \( a \approx 0.5 - 2.5 \)
  \( n \approx 2 \) if \( s_w \geq 0.3 \)
  \( m \equiv \) cementation \( \approx 1.3 \) (Tertiary) – 2.0 (Palaeozoic)
Rock & Mineral Resistivities

• Largest range of values for all physical properties.
• Native Silver = $1.6 \times 10^{-8}$ Ohm-m (Least Resistive)
• Pure Sulphur = $10^{16}$ Ohm-m (Most Resistive)

Table 12.1 Resistivities of some rocks and minerals

<table>
<thead>
<tr>
<th>Rocks, minerals, ores</th>
<th>Resistivity (ohm-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sediments</strong></td>
<td></td>
</tr>
<tr>
<td>chalk</td>
<td>50–150*</td>
</tr>
<tr>
<td>clay</td>
<td>1–100</td>
</tr>
<tr>
<td>gravel</td>
<td>100–5000</td>
</tr>
<tr>
<td>limestone</td>
<td>50–10^7</td>
</tr>
<tr>
<td>marl</td>
<td>1–100</td>
</tr>
<tr>
<td>quartzite</td>
<td>10–10^8</td>
</tr>
<tr>
<td>shale</td>
<td>10–1000</td>
</tr>
<tr>
<td>sand</td>
<td>500–5000</td>
</tr>
<tr>
<td>sandstone</td>
<td>1–10^8</td>
</tr>
<tr>
<td><strong>Igneous and metamorphic rocks</strong></td>
<td></td>
</tr>
<tr>
<td>basalt</td>
<td>10–10^7</td>
</tr>
<tr>
<td>gabbro</td>
<td>1000–10^6</td>
</tr>
<tr>
<td>granite</td>
<td>100–10^6</td>
</tr>
<tr>
<td>marble</td>
<td>100–10^8</td>
</tr>
<tr>
<td>schist</td>
<td>10–10^4</td>
</tr>
<tr>
<td>slate</td>
<td>100–10^7</td>
</tr>
</tbody>
</table>

**Minerals and ores**
- silver $1.6 \times 10^{-8}$
- graphite, massive ore $10^{-4}$–$10^{-3}$
- galena (PbS) $10^{-2}$–$10^2$
- magnetite ore $1–10^5$
- sphalerite (ZnS) $10^3$–$10^6$
- pyrite $1 \times 100$
- chalcopyrite $1 \times 10^{-5}$–0.3
- quartz $10^{10}$–$2 \times 10^{14}$
- rock salt $10^{-13}$

**Waters and effect of water and salt content**
- pure water $1 \times 10^6$
- natural waters $1–10^3$
- sea water 0.2
- 20% salt $5 \times 10^{-2}$
- granite, 0% water $10^{10}$
- granite, 0.19% water $1 \times 10^6$
- granite, 0.31% water $4 \times 10^3$

*Values or ranges, which have come from several sources, are only approximate.
General Rules of Thumb For Resistivity

Highest R

Igneous Rocks
Why? Only a minor component of pore water

Metamorphic Rocks
Why? Hydrous minerals and fabrics

Sedimentary Rocks
Why? Abundant pore space and fluids

Clay: super low resistivity

Lowest R
General Rules of Thumb For Resistivity

Highest R

Older Rocks

Why? More time to fill in fractures and pore space

Lowest R

Younger Rocks

Why? Abundant fractures and/or pore space
Subsurface Current Paths

- About 70% of the current applied by two electrodes at the surface stays within a depth equal to the separation of the electrodes.
- Typically your electrode spacing is 2x your target depth.
  - But this depends on array type (we’ll cover this later).
**Subsurface Current Paths**

- Why does electricity spread out and follow a curved path in the subsurface?
  - A thin layer has a large resistance
  - Electricity follows the path or area of least resistance

\[ R = \rho \frac{l}{a} \]
A Typical Resistivity Meter

- A resistivity meter consists of both a voltmeter and a current meter (ammeter).
- Most systems report the ratio $V/I$ instead of each one separately
  - Gives the resistance
  - The resistance can then be converted into resistivity using geometrical parameters based on the type of array. (We’ll come back to this...)

A resistivity meter is basically a current meter and voltmeter all in one.
How Many Electrodes?

- Most modern resistivity systems typically utilize at least four electrodes
  - Large (and unknown) contact resistance between the electrode and the ground could otherwise give inaccurate readings.
  - To understand why four electrodes are better than two, let's look at the circuit setup...
A Circuit Model
A Circuit Model

[Diagram of a circuit model with labeled resistors and components]
Note: the Voltmeter has an infinite resistance so we can add 2Rc to it without error (eliminate each Rc on the right branch). This leaves us with R=V/I
Typical Resistivity Stats

- The applied voltage (to the current electrodes) is \(~100\) V
- \(\Delta V\) (at the potential electrodes) \(\approx\) millivolts \(\rightarrow\) a few volts
- Current: milliamps or less
  - So you can get a shock, but it is not dangerous
- Current flow is reversed a few times per second to prevent ion buildup at electrodes
Vertical Electrical Sounding

• Resistivity surveys do not usually seek to determine the resistivity of some uniform rock
  – They seek to determine the “apparent resistivity” of several horizontal layers with different resistivities
• Also called “VES”, depth sounding, or electrical drilling
• The essence of VES is to expand electrodes from a fixed center
  – I.e. to increase at least some of the electrode spacings
  – Larger spacings cause electricity to penetrate deeper into the ground
• To understand VES, lets look at some current paths...
Vertical Electrical Sounding

- When electrode spacing is small compared to the layer thickness...
  - Nearly all current will flow through the upper layer
  - The resistivities of the lower layers have negligible effect
    - The measured apparent resistivity is the resistivity of the upper layer

But what happens when a flowing current encounters a layer with a different resistivity?

Refraction!!!
**Current Refraction**

- Current Refracts towards the normal when going into a layer with greater resistivity
  - Not the same as Snell’s Law!
    - This is opposite behavior from seismic refraction (unless you think in terms of a conductivity change)
  - The relationship is: \( \rho_1 \tan \theta_1 = \rho_2 \tan \theta_2 \)
Current Refraction

• Because refraction changes the distribution of current in a layered subsurface
  – The ratio of V/I changes
  – We can therefore measure changes in resistivity with depth
Apparent Resistivity

- In a VES survey the ratio V/I is measured with increasing electrode spacing...
  - The ratio changes for two reasons:
    1. Layers of differing resistivity are encountered
    2. The electrodes are now farther apart
      - Causes measured resistance to decrease!
  - To determine #1, we must first correct for #2
Apparent Resistivity

• Current diverges at one electrode and converges at the other.
  – Current flow lines trace out a banana-like shape.
• Recall that \( R \) is directly proportional to length and inversely proportional to cross sectional area.
• At depth 2d:
  – The length of the path is doubled.
  – The cross sectional length is doubled in both dimensions, so area is 4x.
  – The measured resistance (V/I) will be \( \frac{1}{2} \) as much.

\[
R = \rho \frac{l}{a} = \rho \frac{2l}{4a} = \frac{1}{2} \rho \frac{l}{a}
\]
Apparent Resistivity

• To account for the effects of changes in electrode spacing, the apparent resistivity is found as:

\[ \rho_a = \alpha \frac{V}{I} \]

• Here, \( \alpha \) is a “geometrical factor”
  – equal to \( a/l \) for a rod (see previous slides)
  – The geometrical factor varies depending on array configuration / type
    • I’ll show some common array types later

• For reasons that you will soon see, apparent resistivity \( \rho_a \) is what is typically used
Wenner Arrays

- Pronounced “Venner”. This is the most commonly used in the U.S.
- All four electrodes are equally spaced. Spacing = $a$
- Geometrical correction factor = $2\pi a$
- Measure resistance ($V/I$)
- Calculate apparent resistivity

$$\rho_a = 2\pi a \frac{V}{I}$$

- Repeat for a range of spacings
Wenner VES Survey

• Two measuring tapes are laid out

• Spacing is increased progressively (Gives nearly constant spacing in Log space)
  – 0.1, 0.15, 0.2, 0.3, 0.4, 0.6, 0.8, 1, 1.5, 2, 3, 4, 6 etc...see book (pg 188)

• The survey is stopped when a desired depth is reached
  – Depth \( \approx \frac{1}{2} \) outer electrode distance

• To be efficient, many people are needed

• Modern systems use lots of electrodes
  – Computer does switching
  – Mimics various array types
Wenner VES Survey

- Results of $\rho_a$ are plotted as $\log_{10}\rho_a$ versus $\log_{10}a$
  - Use logs to help accommodate the large range in values

For a simple two layer scenario: (multiple layers are more complex)

- The first few spacings:
  - Electrical current mostly flows in the upper layer
  - So the apparent resistivity is the actual resistivity of the upper layer

- At spacings that are large compared to layer 1’s thickness:
  - Most of the length that the current travels is in the lower layer
  - So the apparent resistivity is the resistivity of the lower layer

How do we determine layer thickness?
Wenner VES Survey

- To determine layer thickness
- Note that the left curve reaches the lower layer’s resistivity sooner
  - So, all other factors equal, the first layer must be thinner
- In practice, determining thickness is not so easy because how quickly you reach the lower layer’s resistivity also depends on the resistivity contrast
  - Large resistivity contrasts have a similar effect to thinner layers and vice versa.
- Resistivities and thicknesses are instead best found by using “Master curves” that are calculated for different values of thickness and resistivity
Wenner Array Master Curves: 2-Layer Case

- To reduce the number of graphs needed, master curves are normalized on both axes. Plotted in Log-Log space
  - Overlay your data on a master curve and find the curve that matches

\[ \rho_a = \text{calculated apparent resistivity} \]
\[ \rho_1 = \text{resistivity of top layer} \]
\[ a = \text{electrode separation} \]
\[ h = \text{thickness of top layer} \]

Both plots **MUST BE THE SAME SCALE**!

I.e. a change in log of 1 on each data axis must match the master curve’s change of 1 log on each axis

\[ \frac{\rho_a}{\rho_1} = 1 \]
\[ \frac{\rho_a}{\rho_1} = \infty \]
\[ \frac{\rho_a}{\rho_1} = 0 \]

\[ \frac{a}{h_1} = 1 \]
\[ \frac{a}{h_1} = 0 \]

\[ \rho_a, \rho_1 \]
Master Curve: 2-Layer Example

- To determine the resistivities of a two layer system:
  - Make a plot of $\log_{10} a$ (electrode spacing) vs. $\log_{10} \rho_a$ (apparent / measured resistivity)
  - Scale the plots to be the same size
    - So a $\log_{10}$ change of 1 on your graph is the same size as the master curve
    - Slide your data around until you find a curve that it best matches
    - Find the $a/h_1$ line on the master curve. Where this crosses your data’s x-axis is the layer thickness.
    - Find the $\rho_a / \rho_1$ line on the master curve. Where this crosses your data’s y-axis is the resistivity of the first layer.
    - The resistivity of the second layer can be found by multiplying the first layer’s resistivity by the best-fitting curve’s $\rho_a / \rho_1$ ratio

Illustrator Demo
Master Curve: 2-Layer Example

- So for this data:
  - The data best fit the $\rho_a / \rho_1 = 6$ master curve
  - $h_1 = 0.2$ m
  - $\rho_1 = 18.9$ ohm-m
  - $\rho_2 = 18.9 \times 6 = 113$ ohm-m
Multiple Layers

- If there are more than two layers:
  - The plot probably never reaches the resistivity of layer 2 even at large separations.
    - Increasing spacing penetrates into layer 3.
  - Visual inspection can tell how many layers are present.
    - Each kink or curvature change shows the presence of a new layer
    - But this is only a minimum. Some layers may lack large and visible contrasts.

![Diagram of multiple layers](image)
Multiple Layers

- If there are more than two layers:
  - The thicknesses and resistivities of each layer are modeled using computer programs.
    - The program guesses at the number of layers and makes a theoretical plot.
    - Parameters are changed until a satisfactory fit is achieved.

(a) apparent resistivity plot

(b) model
Other Array Types

- Lots of other resistivity arrays exist.
- Schlumberger is commonly used (especially in Europe)
  - Only C electrodes are moved
  - Saves time!
  - Eventually $\Delta V$ becomes small
  - P electrodes are moved and then process is repeated
- Each has its own set of master curves and software
The BGS Offset Wenner Array System

- Multi-electrode arrays are now commonly used.
  - A computer-controlled switch box turns electrodes on-off
  - Can get a lateral and vertical data in one step
  - Can also assess error and lateral variations.

(a) 

(b) 

(1) 

(2) 

(3) 

(4) 

(5) 

(c) 

A: C P P C
C: C P C P
D₁: C P P C
D₂: C P P C
B: C P C P
VES Limitations

- Maximum depth of detection depends on:
  - Electrode spacing (rule of thumb depth = \( \frac{1}{2} \) C electrode spacing)
  - Resistivity contrasts between layers
  - Limits of detection of small \( \Delta V \)
    - Low-resistivity layers result in \( \Delta V \) becoming very small
    - Large spacings cause \( \Delta V \) to become small

- Layers may have spatially-variable resistivities
  - If so, electrical profiling may be a better choice
  - If not, you can interpolate lateral continuity
VES Limitations

- Layers may have anisotropic resistivity
  - Resistivity may be much greater perpendicular to layering
    - e.g. bedding, laminations, foliation
  - Horizontal laminations cause layer thicknesses to be overestimated

- Sandwiched thin layers produce non-unique results due to refraction
  - If middle unit has much higher resistivity
    - $t/p$ is constant, so a 2x thicker unit with ½ resistivity would produce the same results.
  - If middle unit has much lower resistivity
    - $t/p$ is constant, so a 2x thicker layer with 2x resistivity would produce the same results
  - Called ‘equivalence’
Electrical Profiling

• Lateral changes in resistivity can be effectively mapped using electrical profiling.
  – Can use similar arrays to VES
  – Patterns vary depending on what array is used
  – Patterns are complicated because electrodes may be in zones of different properties.
Electrical Imaging

- Because resistivity may vary both laterally and vertically, neither VES or electrical profiling may give the desired results.
- To image lateral and vertical changes, electrical imaging is used
  - Involves expanding and moving arrays
  - produces a pseudosection
    - pseudosections do not reveal the actual properties, but do show useful patterns
Pseudosection ---> True Section

• With the aide of computers, pseudosections can be converted into approximately ‘true sections’

Caveats:
• edges are blurred
• actual contrasts are underestimated

(a) pseudosection

(b) ‘true’ section

Wenner array: minimum electrode a spacing 20 m
distance along traverse (m)

depth (m)

rectangular block

resistivity (ohm-m)
Final Remarks

• **Like all geophysical techniques resistivity:**
  – Produces non-unique results
    • Data should be compared to known geological data (e.g. boreholes)
    • Similar rocks have a wide range in resistivities depending on water content
    • Lithology changes do not necessarily correspond to a resistivity change
    • Resistivity changes do not necessarily correspond to a lithology change
  – So, without sound geological knowledge, resistivity data may be misleading.