Electrical properties of rocks - Key points

- Electrical resistivity and conductivity
  - Relations to porosity, water content, and bedding
  - Archie's law
- Dielectric properties
  - Relations to porosity, water content, and bedding
  - Electromagnetic wave speeds

- Reading:
  - Reynolds, Sections 7.1-7.2
  - Dentith and Mudge, Sections 5.1 – 5.3

Electrical properties of rocks

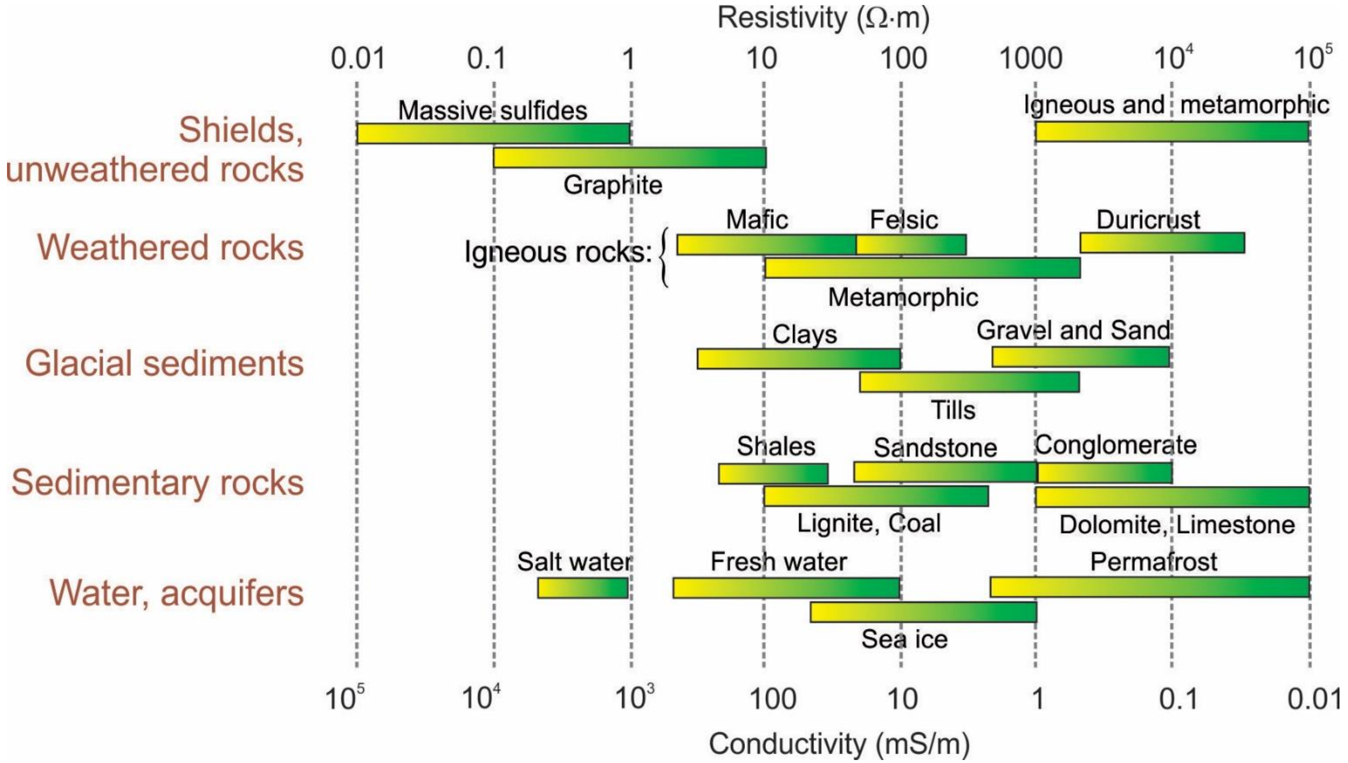
- In the following, let us consider the key electric material properties in some detail:
  - Resistivity (ρ) and conductivity (σ)
    - These are measured in "resistivity" experiments. See lecture on resistivity method.
  - Dielectric constants ε
    - They are accessed in SP and IP measurements. Also see lecture on these methods.
- For both of these electric properties, we will be interested in their relations to rock structure such as porosity, layering, mineral content, and pore fluids

Conduction of electrical current in rock

- Resistivity measurements are used to identify conditions within rock by the values of conductivity σ or resistivity $\rho = 1/\sigma$. The common criteria are:
  - For completely dry rick with no metallic content – σ is very low
    - …Same with high metallic content and connectivity – σ is high
      - …Same with poor connectivity – σ is low
  - For water-saturated (usually saline) rock – σ is high
  - For oil/gas saturated rock – σ is low
- For non-metallic materials, conductivity is typically due to the presence of electrolyte (mechanisms supporting ionic or electronic conduction between molecules)
  - Electrolytes are usually due to salts dissolved in water
  - However, even dry rock can work as electrolyte:
    - (SiO_4) - big immobile ion;
    - Na^+, K^+, Mg^{++}, Fe^{++}, Al^{++} - small mobile ions.
- Resistivity varies greatly in geological materials:
  - From $1.6\cdot10^{-8}\Omega m$ (silver) to $10^{16}\Omega m$ (pure sulphur)
  - With age: from 10-200 $\Omega\cdot m$ for Quaternary volcanics to 1000-2000 $\Omega\cdot m$ for Precambrian

Ranges of electrical resistivity and conductivity

- This diagram was already shown in Introduction
- Also see lists in the next slide and in the course text



More detail on resistivities of rock

Resistivity ranges

Rock type	Resistivity range (Ωm)
Granite porphyry	4.5×10^3 (wet) – 1.3×10^6 (dry)
Feldspar porphyry	4×10^3 (wet)
Syenite	$10^2 - 10^6$
Diorite porphyry	1.9×10^3 (wet) – 2.8×10^4 (dry)
Porphyrite	10 – 5 [illegible]
Carbonatized porphyry	2.5×10[illegible] (wet) – 6×10[illegible] (dry)
Quartz diorite	$2 \times 10^4 - 2 \times 10^6$ (wet) – 1.8×10^5 (dry)
Porphyry (various)	$60 - 10^4$
Dacite	2×10^4 (wet)
Andesite	4.5×10^4 (wet) – 1.7×10^2 (dry)
Diabase (various)	$20 - 5 \times 10^7$
Lavas	$10^2 - 5 \times 10^4$
Gabbro	$10^3 - 10^6$
Basalt	$10 - 1.3 \times 10^7$ (dry)
Olivine norite	$10^3 - 6 \times 10^4$ (wet)
Peridotite	3×10^3 (wet) – 6.5×10^3 (dry)
Hornfels	8×10^3 (wet) – 6×10^7 (dry)
Schists (calcareous and mica)	$20 - 10^4$
Tuffs	2×10^3 (wet) – 10^5 (dry)
Graphite schist	$10 - 10^2$
Slates (various)	$6 \times 10^2 - 4 \times 10^7$
Gneiss (various)	6.8×10^4 (wet) – 3×10^6 (dry)
Marble	$10^2 - 2.5 \times 10^8$ (dry)
Skarn	2.5×10^2 (wet) – 2.5×10^8 (dry)
Quartzites (various)	$10 - 2 \times 10^8$
Consolidated shales	$20 - 2 \times 10^3$
Argillites	$10 - 8 \times 10^2$
Conglomerates	$2 \times 10^3 - 10^4$
Sandstones	$1 - 6.4 \times 10^8$
Limestones	$50 - 10^7$
Dolomite	$3.5 \times 10^2 - 5 \times 10^3$
Unconsolidated wet clay	20
Marls	3 – 70
Clays	1 – 100
Oil sands	4 – 800

Effects of water content and salinity

- Resistivity of porous rock strongly depends on its water content (table on the right)
  - Specifically, rock resistivity is proportional to the resistivity of pore water and a power of porosity (Archie's law, next slide)
- Water resistivity, ρ_w, in its turn, quickly reduces with salinity
  - Resistivity measurements are often used to measure the salinity of water
- About dependencies on water salinity, see labs #3 and #4
  - Resistivity measurements are often used to derive water salinity

Rock	% H_2O	ρ (Ωm)
Siltstone	0.54	1.5×10^4
Siltstone	0.38	5.6×10^8
Coarse grain SS (sandstone)	0.39	9.6×10^5
Coarse grain SS	0.18	10^8
Medium grain SS	1.0	4.2×10^3
Medium grain SS	0.1	1.4×10^8
Graywacke SS	1.16	4.7×10^3
Graywacke SS	0.45	5.8×10^4
Arkosic SS	1.0	1.4×10^3
Organic limestone	11	0.6×10^3
Dolomite	1.3	6×10^3
Dolomite	0.96	8×10^3
Peridotite	0.1	3×10^3
Peridotite	0	1.8×10^7
Pyrophyllite	0.76	6×10^6
Pyrophyllite	0	10^{11}
Granite	0.31	4.4×10^3
Granite	0.19	1.8×10^6
Granite	0	10^{10}
Diorite	0.02	5.8×10^5
Diorite	0	6×10^6
Basalt	0.95	4×10^4
Basalt	0	1.3×10^8
Olivine-pyrox.	0.028	2×10^4
Olivine-pyrox.	0	5.6×10^7

Archie's law

- Archie's law describes the dependence of rock resistivity on porosity and pore fluid
  - It holds well for clay-free rocks (with non-conductive matrix)
- For water-saturated rock, resistivity ρ is proportional to the resistivity of pore water, ρ_w and decreases with porosity, ϕ, as:

$$\rho = a\rho_w\phi^{-m}$$

where a and m are empirical constants.

m is the cementation exponent depending on the degree of consolidation. Parameter a is called tortuosity, which measures the shape and connectivity of the pore volume

  - Note that there is no particular physics behind the power-law dependence on ϕ. It is merely an empirical linear relation between logarithmic quantities:

$$\log\left(\rho / \rho_w\right) = const - m\log\phi$$

- Typical values are $a \approx 1$ and $m \geq 1$ with:
  - $m = 1$ for hypothetical, parallel cylindrical pores;
  - $m \approx 1.3$ for packed spheres;
  - $m \approx 2$ for sandstone.
- The ratio $\rho / \rho_w = a\phi^{-m}$ is called the (electrical) Formation Factor (see lab #4)

Archie's law for partial saturation

- For rock above the water table, pores will be only partially filled with water. An additional factor is included in Archie's law to account for partial water saturation:

$$\rho = a\rho_w \phi^{-m} s_w^{-n}$$

where the saturation s_w is the fraction of total volume of pores filled with electrolyte

- Generally, a is around one, and $n \approx 2$ for $s_w > s_{wc}$, where the critical saturation, s_{wc}, is the one for which a continuous film of water covers all surfaces within the rock
- Typical values of s_{wc} are 25% for sandstone, 75% for granite.
- For low saturation $s_w < s_{wc}$, resistivity decreases with s_w faster: $n \approx 4$ to 5, and dependence on porosity is less important:

$$\frac{\rho}{\rho\left(s_w = 100\%\right)} = b s_w^{-n}$$

Dielectric constants

- Note that dielectric constants vary by about an order of magnitude for different rocks
  - The highest for water
  - Thus, water is a highly polarizable substance

Rock, mineral	Dielectric const.
Galena	18
Sphalerite	7.9 – 69.7
Cassiterite	23
Hematite	25
Fluorite	6.2 – 6.8
Calcite	7.8 – 8.5
Apatite	7.4 – 11.7
Barite	7 – 12.2
Peridotite	8.6
Norite	61
Quartz porphyry	14 – 49.3
Diabase	10.5 – 34.5
Trap	18.9 – 39.8
Dacite	6.8 – 8.2
Obsidian	5.8 – 10.4
Sulphur	3.6 – 4.7
Rock salt	5.6
Anthracite	5.6 – 6.3
Gypsum	5 – 11.5
Biotite	4.7 – 9.3
Epidote	7.6 – 15.4
Plagioclase feldspar	5.4 – 7.1
Quartz	4.2 – 5
Granite (dry)	4.8 – 18.9
Gabbro	8.5 – 40
Diorite	6.0
Serpentine	6.6
Gneiss	8.5
Sandstone (dry to moist)	4.7 – 12
Packed sand (dry to moist)	2.9 – 105
Soil (dry to moist)	3.9 – 29.4
Basalt	12
Clays (dry to moist)	7 – 43
Petroleum	2.07 – 2.14
Water (20°C)	80.36
Ice	3 – 4.3

Dielectric permittivity and anisotropy of porous rock

- Like resistivity in Archie's law, dielectric permittivity is related to porosity, water content, and also to bedding direction
  - For electrical filed parallel to bedding, the permittivity is an arithmetic mean of permittivities of the rock matrix (ε_m) and pore water (ε_w):

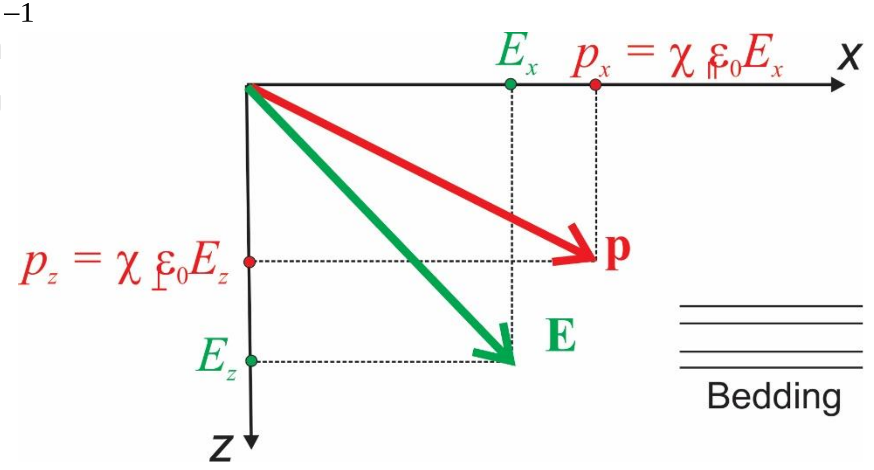
$$\varepsilon_{\parallel} = (1-\phi)\,\varepsilon_m + \phi\varepsilon_w$$

(This is because the tangential component of E is continuous across the bedding)

  - For electrical filed perpendicular to bedding, the permittivity is a harmonic mean of the permittivities of the components:

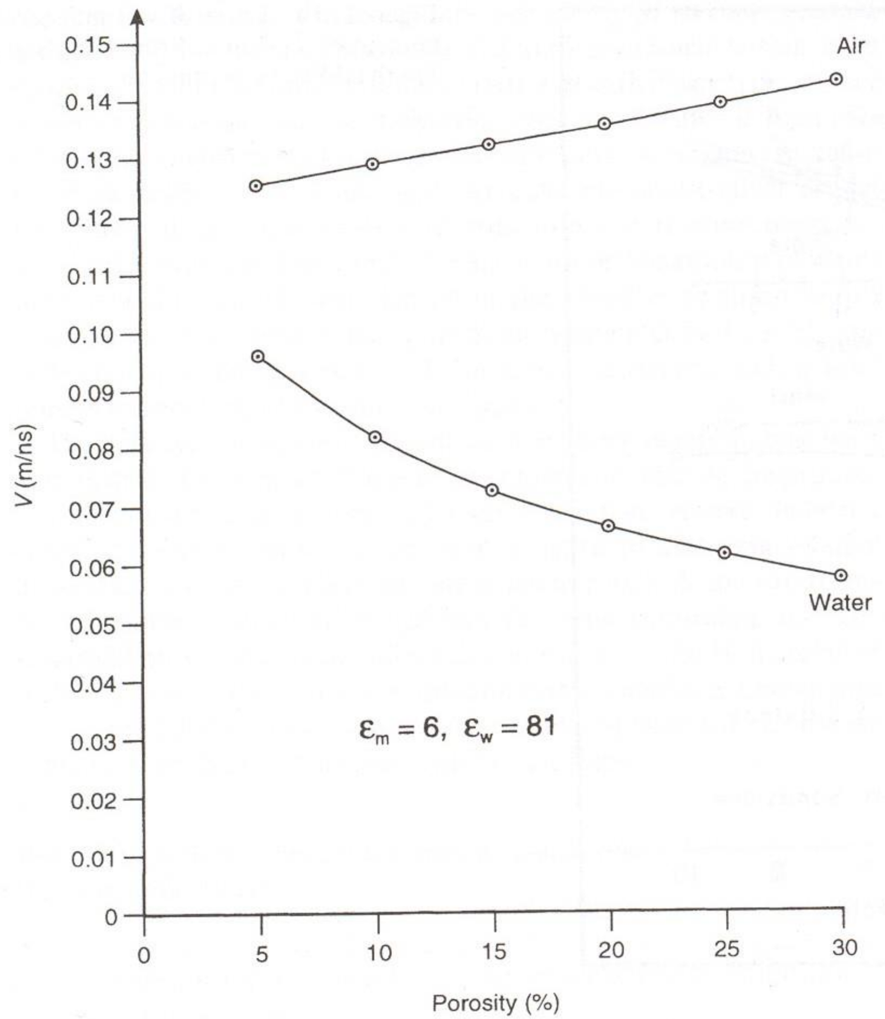
$$\varepsilon_{\perp} = \left(\frac{1-\phi}{\varepsilon_m} + \frac{\phi}{\varepsilon_w}\right)^{-1}$$

- The difference between $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ leads to strong anisotropy of the electrical response of layered porous subsurface. Note the difference between directions of vectors **E** and **p** (different ε are shown through different polarizabilities χ here):



Effect of porosity on ε and GPR waves

- Sometimes, you may try using Ground Penetrating Radar (GPR) to detect porous or wet zones
  - GPR waves are most sensitive to variations of ε (next slide)
- Because $\varepsilon_w > \varepsilon_m$, the above $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ increase/decrease with ϕ for wet/dry layered rock, respectively.
  - This leads to GPR wave speed changing with porosity (see Figure)
- Because of increasing conductivity (recall Archie's law) also waves experience "attenuation", and penetration depth decreases with porosity for GPR
  - However, the more severe factor reducing GPR penetration in SK tills is the presence of clays



Radio (GPR) wave speeds

- Variable dielectric permittivity is the primary factor controlling the speed of radio (electromagnetic) waves within ground
  - The wave speeds and particularly their contrasts are used in Ground Penetrating Radar (GPR) imaging (see GEOL335 class)
- The relation is: $c \approx \frac{c_{\text{air}}}{\sqrt{\varepsilon}}$
- Thus, with ε varying up to $\varepsilon_w \approx 80$ (for water), c varies by a factor of about 3 – 9.