Physical properties

Reading on the GPG:

https://gpg.geosci.xyz/content/physical_properties/index.html

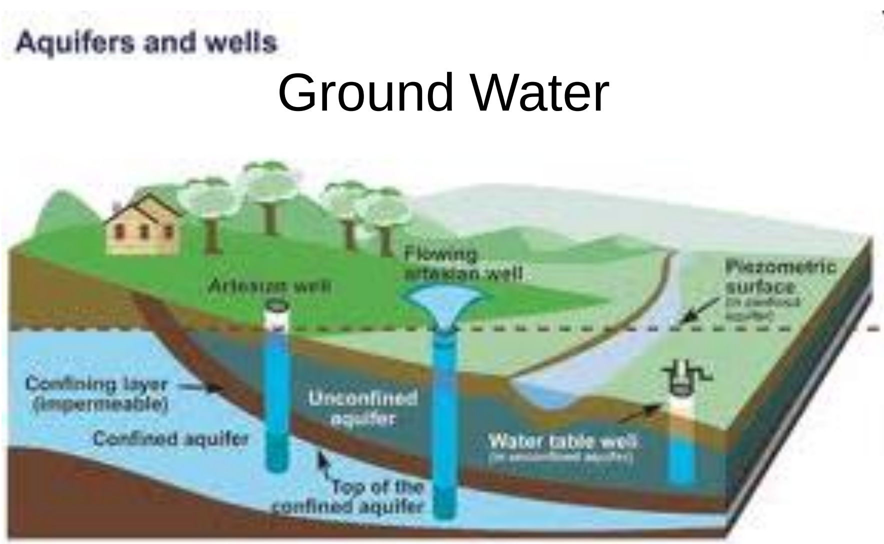
From Last Time

Finding Resources

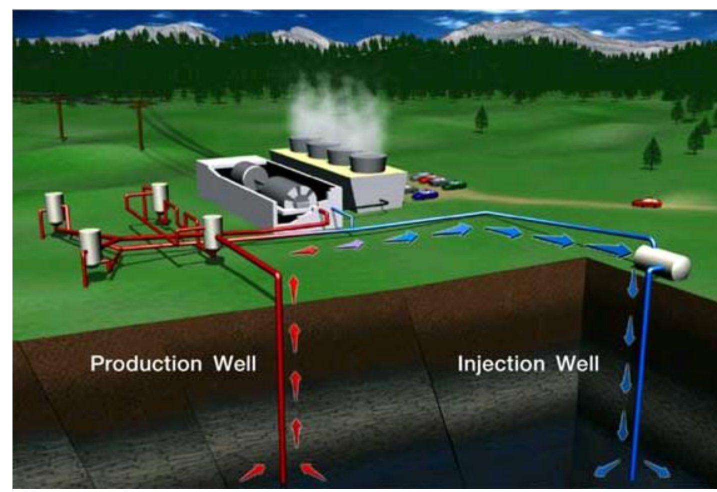
Minerals

Hydrocarbons

Ground Water



Geothermal Energy



Natural Hazards

Volcanoes

Earthquakes

Tsunami

Geotechnical engineering

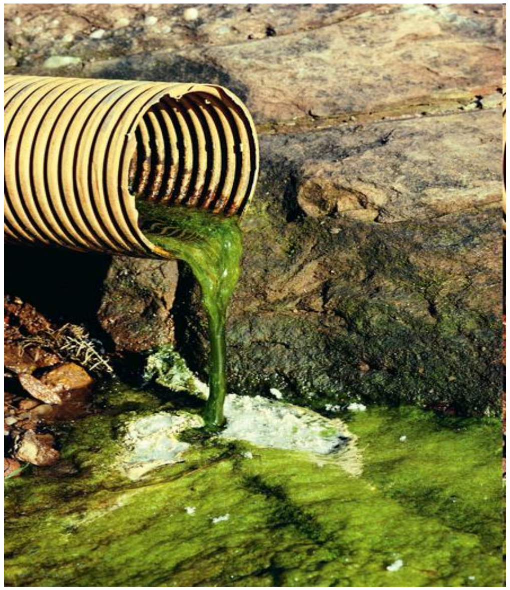
Tunnels

Slope stability

In-mine safety

Environmental

Water contamination

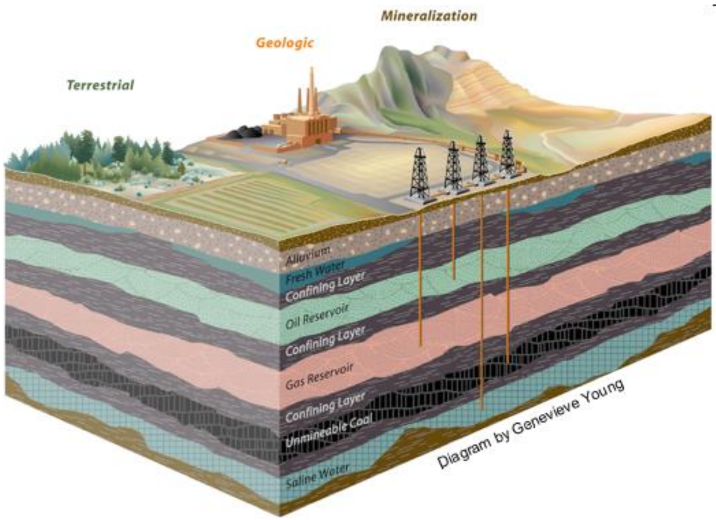


Salt water intrusion

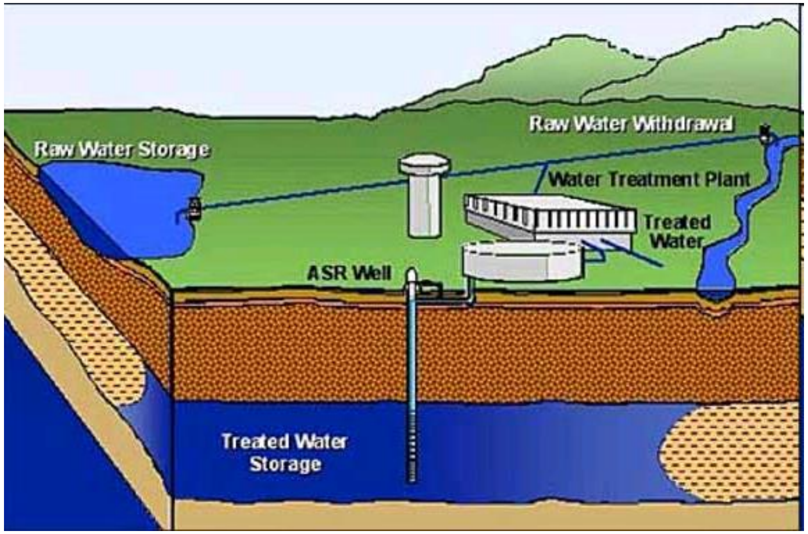
http://www.centennialofflight.gov

Surface or Underground Storage

CO2 sequestration



Aquifer Storage and Recover



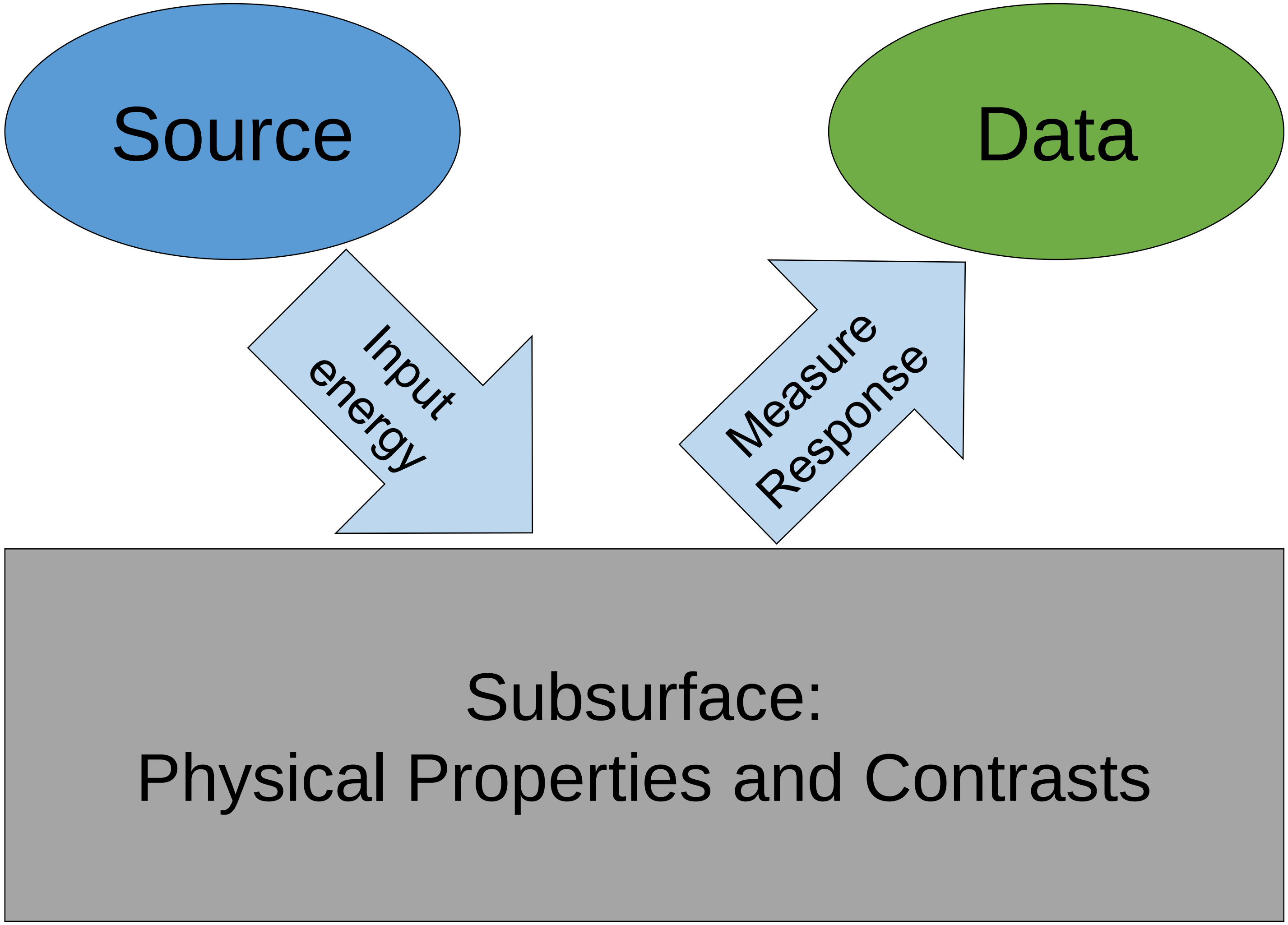
Industrial Waste Disposal

Radioactive Waste

What do all these problems have in common?

- They all require ways to see into the earth without direct sampling.

Geophysical Surveys



Geophysical Methods

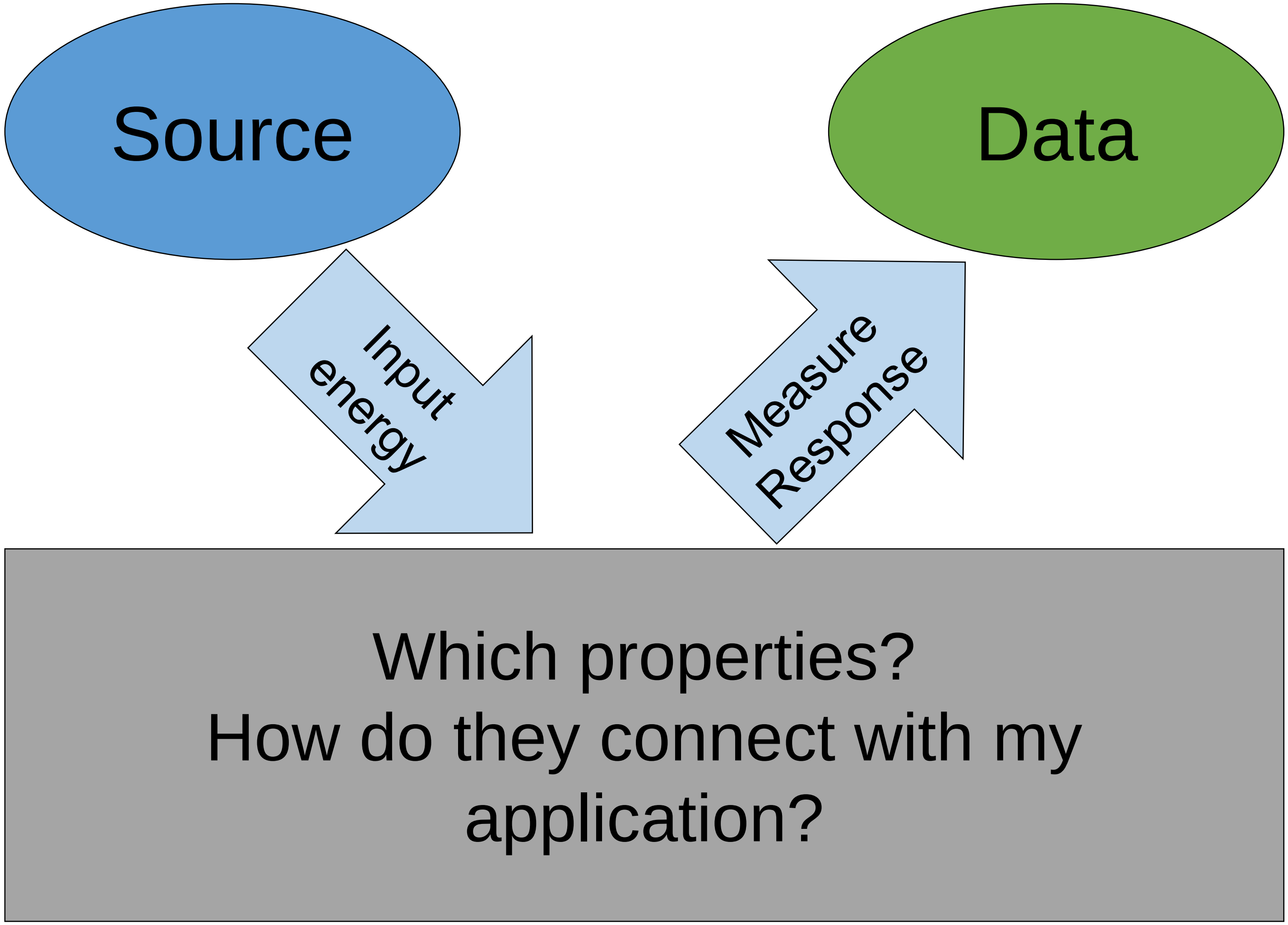
- Geophysical surveys
  - Magnetic (magnetic susceptibility)
  - Seismic (density, elastic parameters)
  - Ground penetrating radar (electrical permittivity)
  - DC resistivity (electrical conductivity/resistivity)
  - Electromagnetic (electrical conductivity/resistivity)
  - Others

- Requires a contrast in physical properties

Today

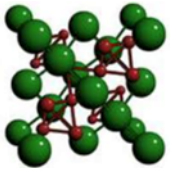
- How do geophysicists differentiate materials?
- What are the different physical properties?
- What is the range of values defining each physical property?
- What factors impact different physical properties?

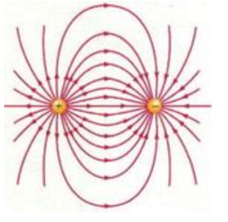
Using Geophysics



How do we differentiate materials?

- Characterize materials by physical properties:
  - Density
  - Magnetic susceptibility
  - Electrical conductivity
  - Chargeability
  - Electrical permittivity
  - Elastic moduli





- If we know the physical properties then we might be able to answer our question…

Density

$$\rho = \frac{m}{V}$$

Density: ρ in g/cm^3 or kg/m^3
Mass: m in g or kg
Volume: V in cm^3 or m^3

Density of earth materials

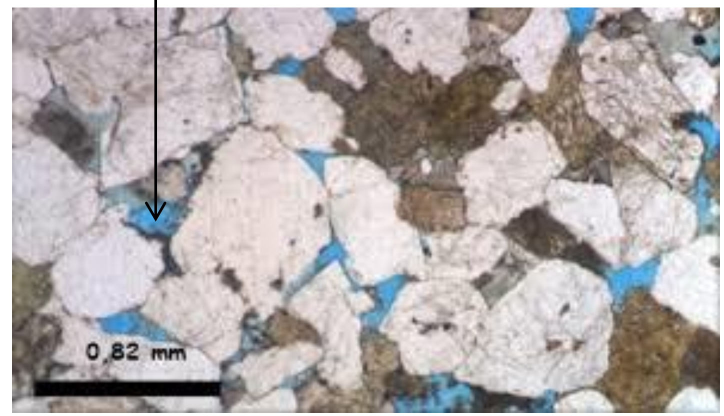
Air:	0.001225 g/cm^3
Water:	1.00 g/cm^3
Ice:	0.917 g/cm^3
Petroleum:	0.60 - 0.90 g/cm^3
Sedimentary Rocks:	1.50 - 3.30 g/cm^3
Igneous Rocks:	2.35 - 3.50 g/cm^3
Metamorphic Rocks:	2.52 - 3.54 g/cm^3
Ore-Bearing Rocks:	2.30 - 7.60 g/

Question: In general, why do sedimentary rocks have lower density compared to other types of rock?

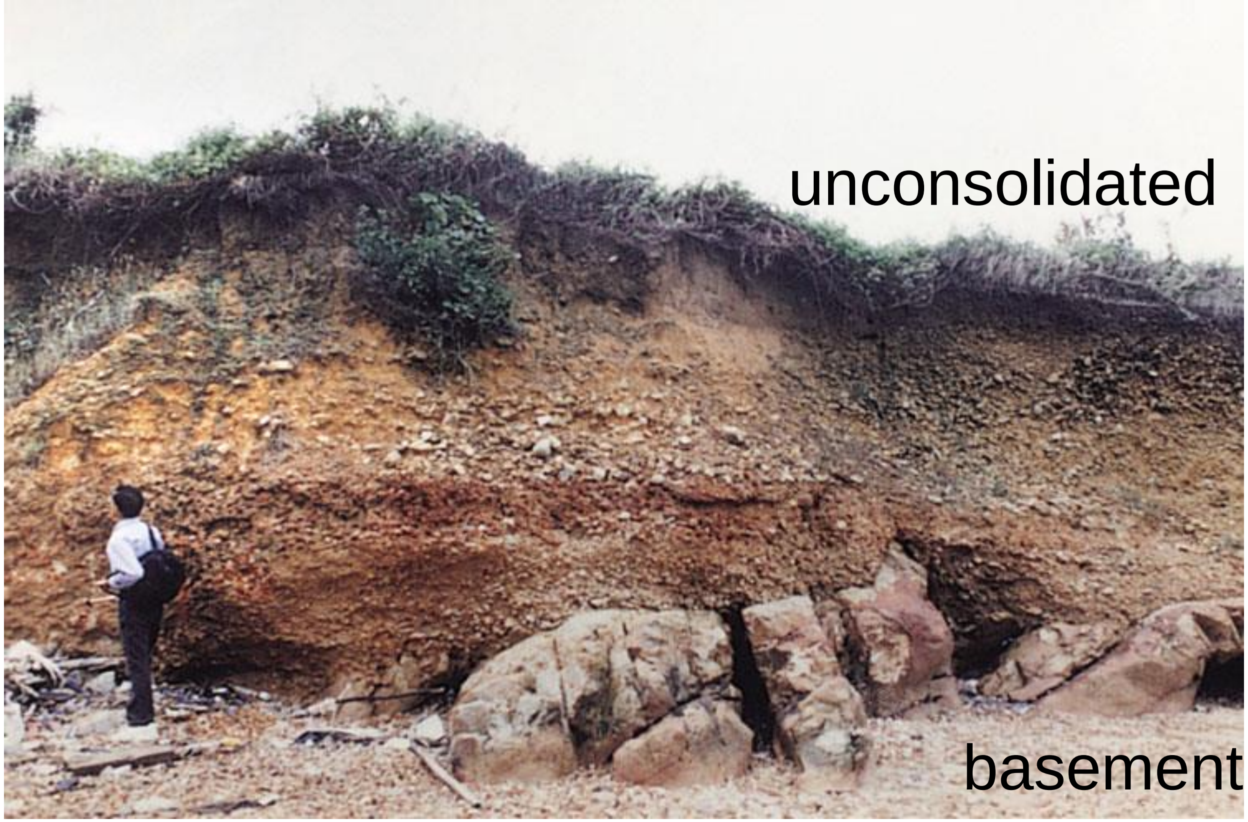
Porous rocks

fluid

bulk density < skeletal densit



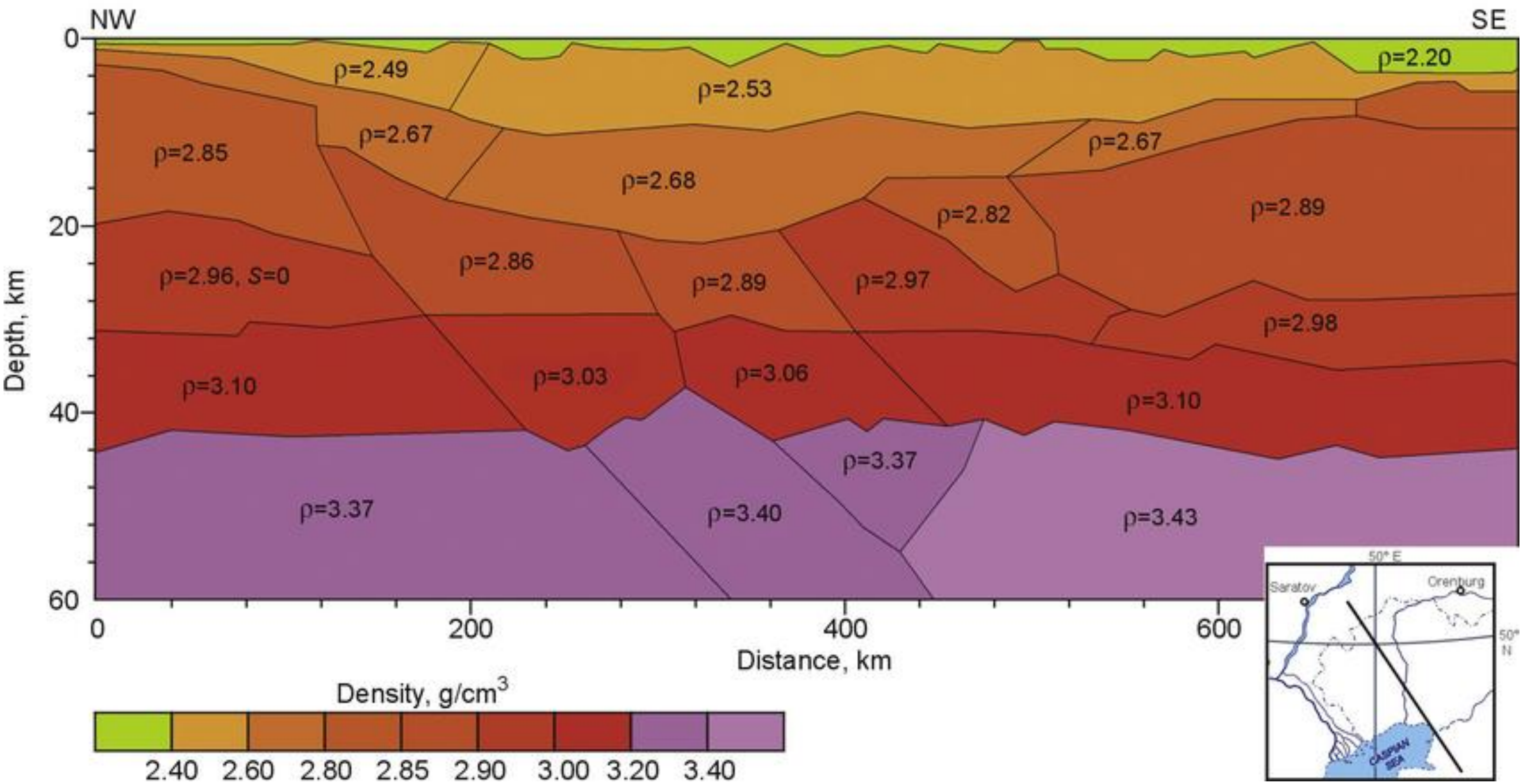
Density vs. depth (pressure)



Low density

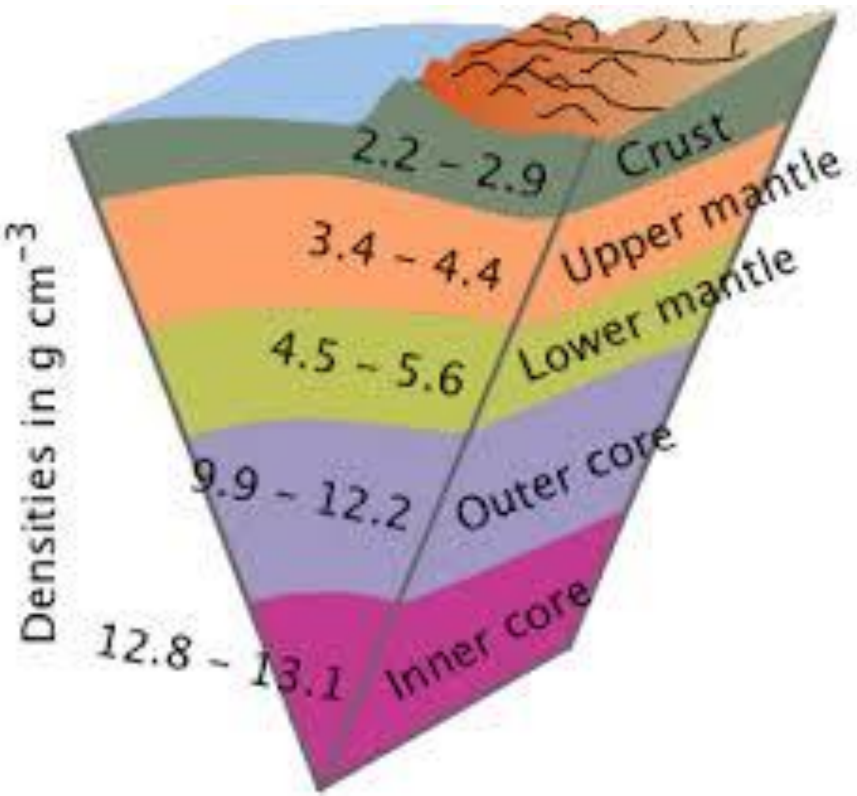
High density

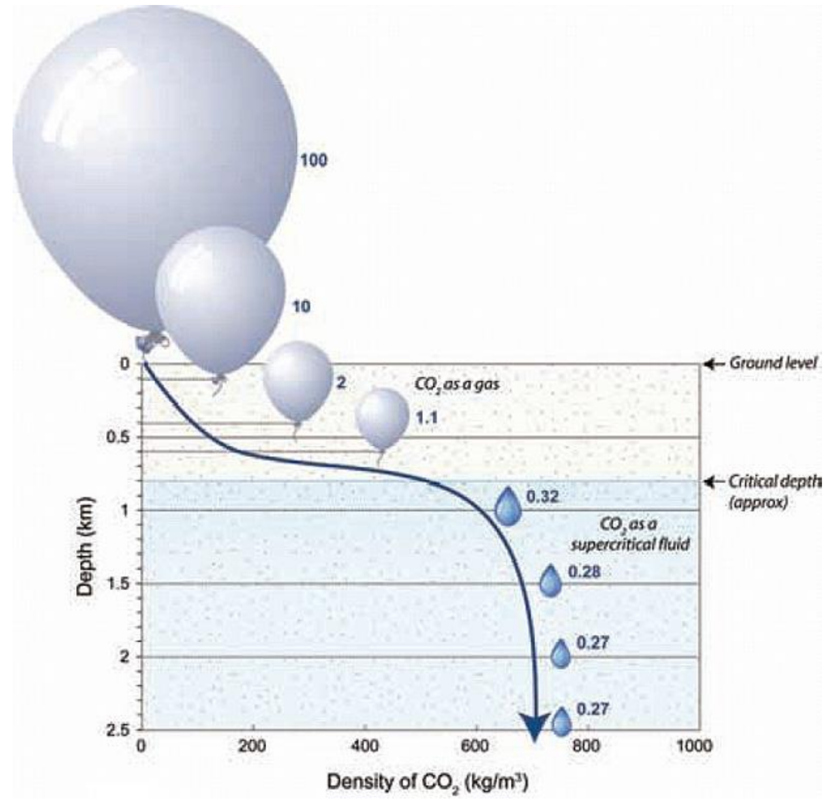
Density vs. depth (pressure)



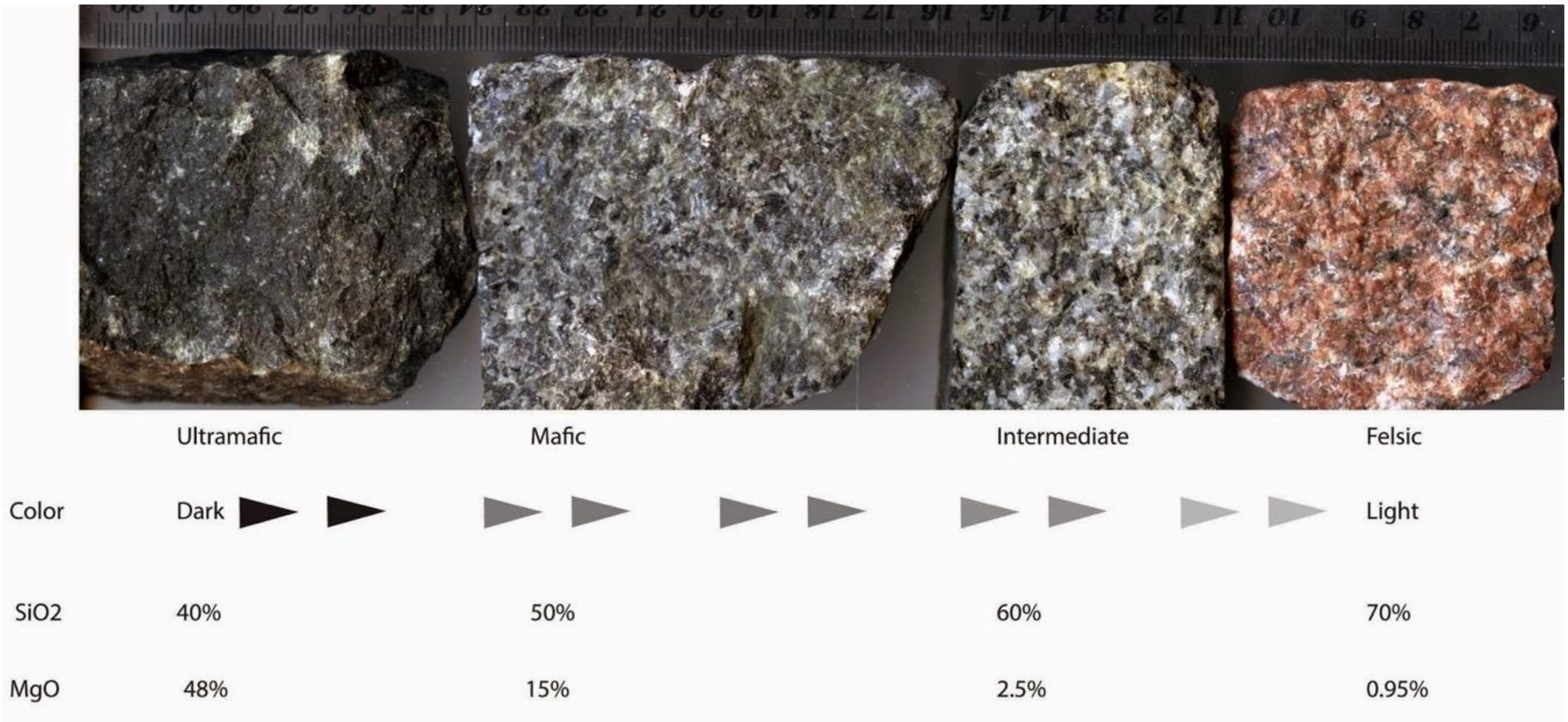
Artyushkov et. al. 2014

Density vs. depth (pressure)



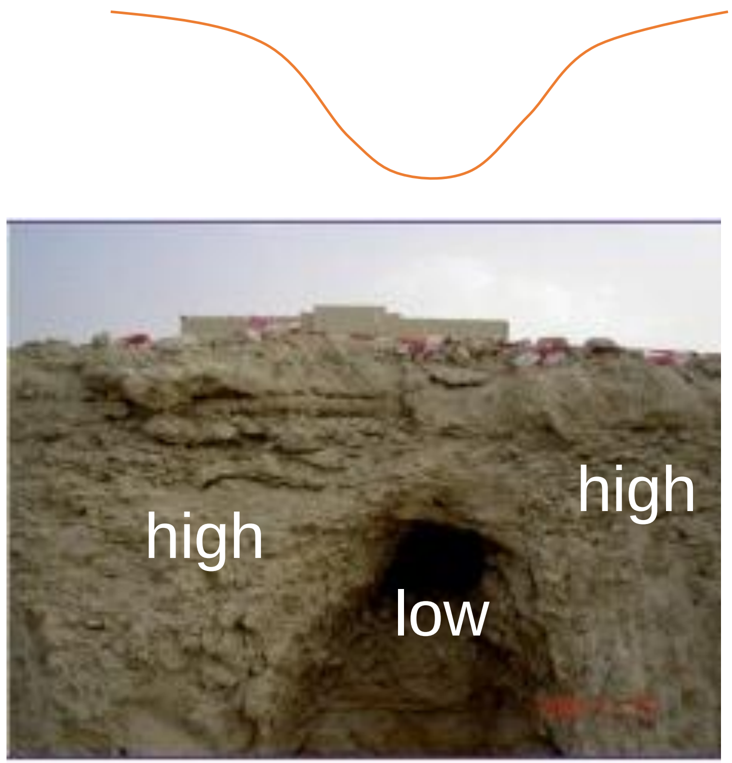


Composition

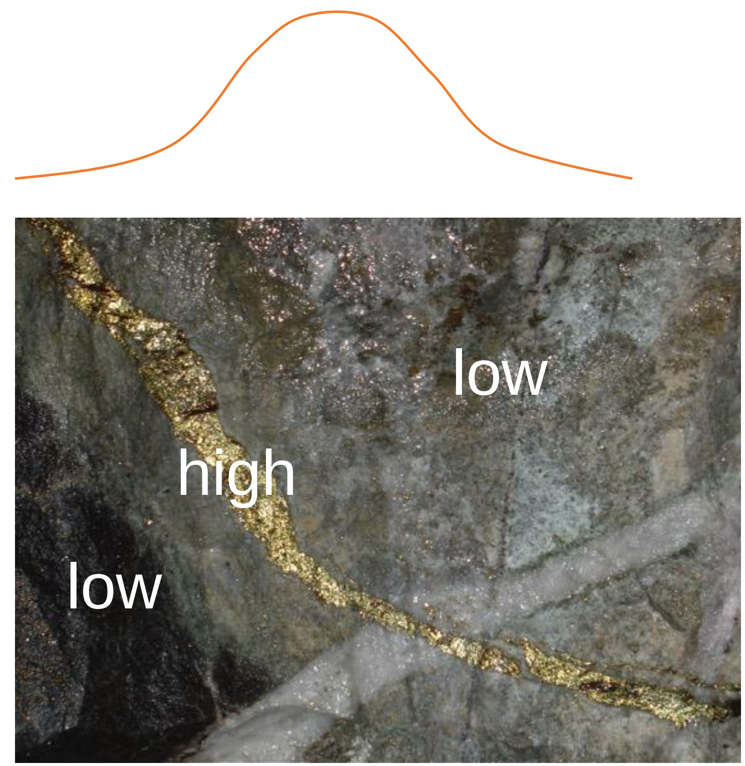


Heavy elements: magnesium, iron, lead, copper, silver, gold …

Gravity exploration

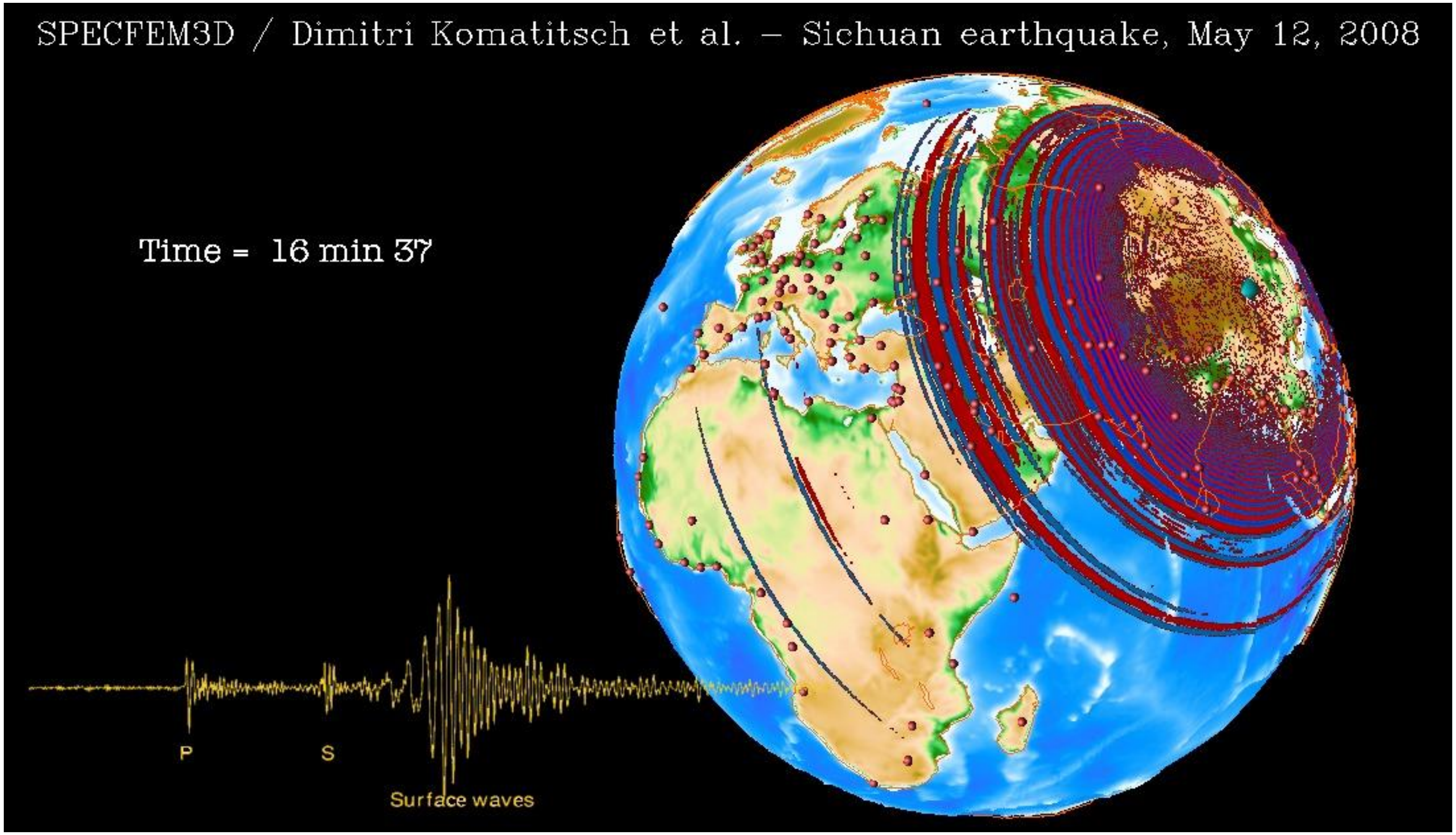


cavity

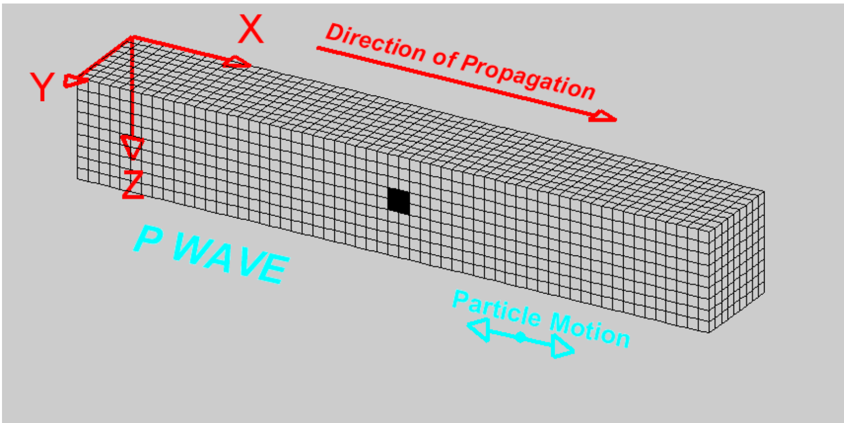


mineralization

Elastic moduli and seismic velocity

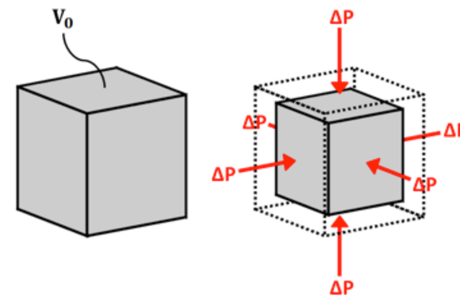


Body waves

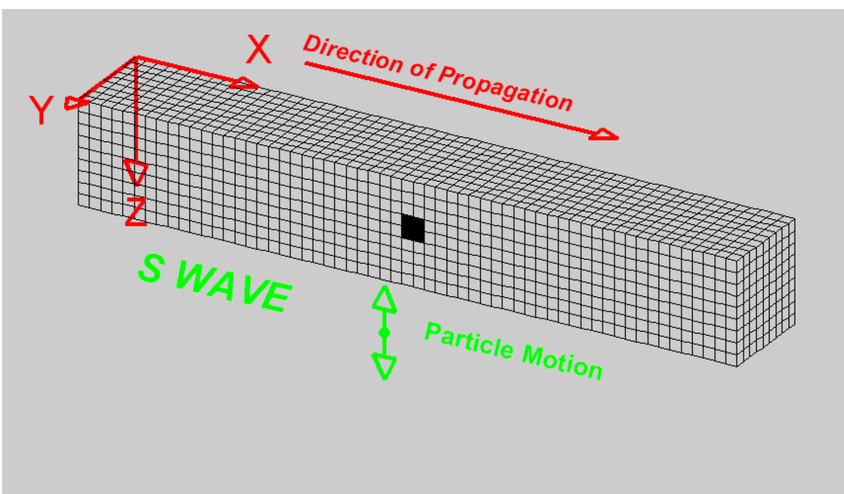


$$v_p = \sqrt{\frac{K + 4/3\mu}{\rho}}$$

bulk modulus
(incompressibility)

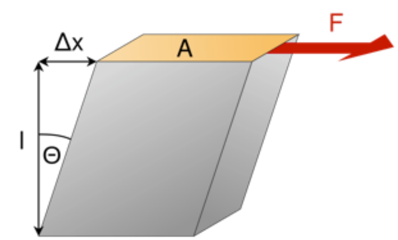


$$K = -V_0 \frac{\Delta P}{\Delta V}$$



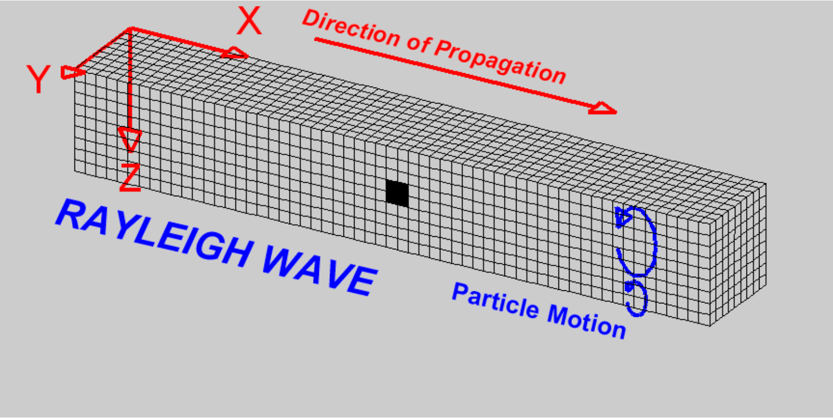
$$v_s = \sqrt{\frac{\mu}{\rho}}$$

shear modulus
(rigidity)

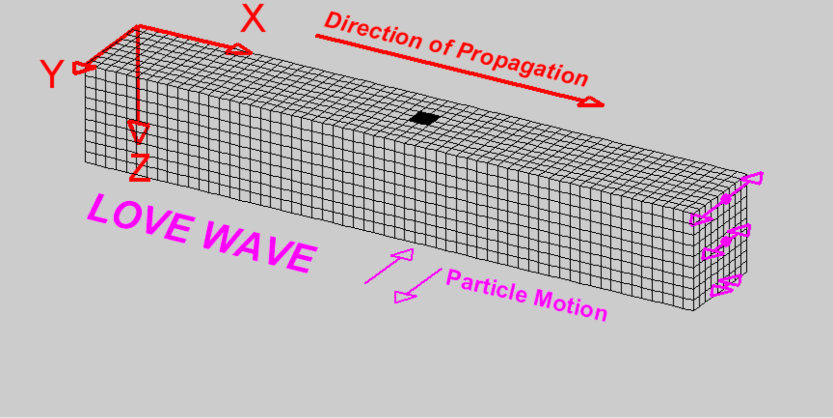


$$\mu = \frac{Stress}{Strain} = \frac{Fl}{\Delta x A}$$

Surface waves



$$v_R = 0.9\, v_s$$



$$0.9\, v_s < v_L < v_s$$

Seismic velocities

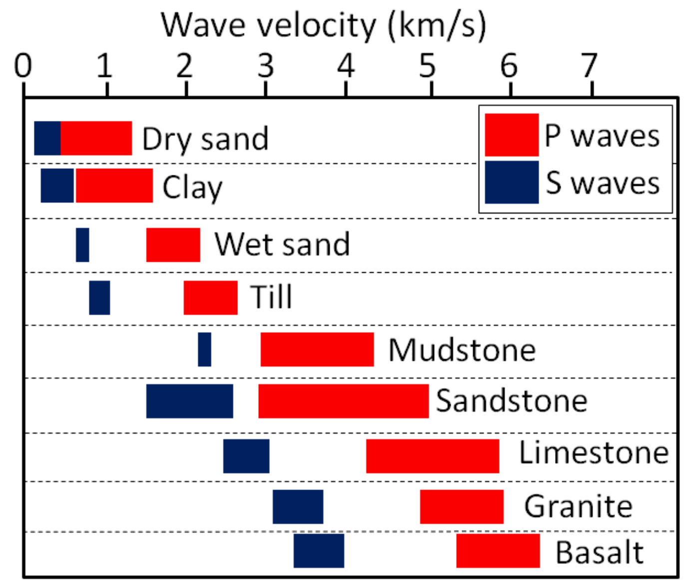
$$v_p = \sqrt{\frac{K + 4/3\mu}{\rho}} \qquad v_s = \sqrt{\frac{\mu}{\rho}} \qquad v_R = 0.9\, v_s \qquad 0.9\, v_s < v_L < v_s$$

Property	Symbol	Units
P-Wave Velocity	v_p	m/s or km/s
S-Wave Velocity	v_s	m/s or km/s
Bulk Modulus(Incompressibility)	K	Pa or GPa
Shear Modulus (Rigidity)	μ	Pa or GPa
Density	ρ	kg/m^3 or g/cm^3

Question: Why don't we just use the intrinsic properties?

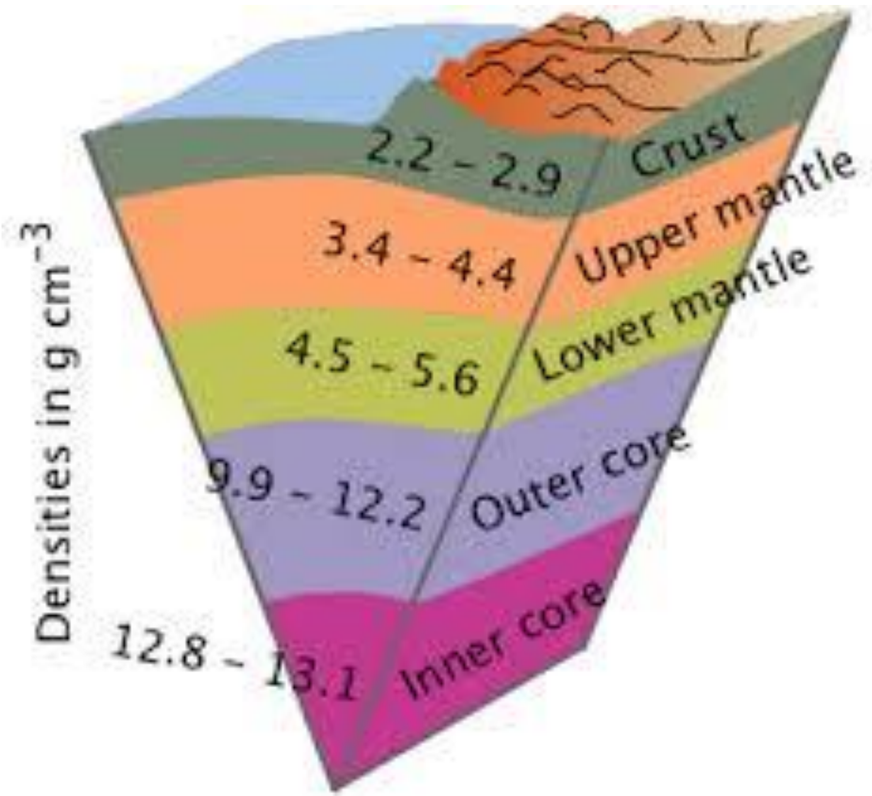
Velocities of common rocks

Material	P-wave (m/s)	S-wave (m/s)
Air	343	N/A
Water	1450 - 1500	N/A
Ice	3400 - 3800	1700 - 1900
Oil	1200 - 1250	N/A
Vegetal Soil	300 - 700	100 - 300
Dry Sands	400 - 1200	100 - 500
Wet Sands	1500 - 2000	400 - 600
Saturated Shales and Clays	1100 - 2500	200 - 800
Porous and Saturated Sandstones	2000 - 3500	800 - 1800
Marls	2000 - 3000	750 - 1500
Chalk	2300 - 2600	1100 - 1300
Coal	2200 - 2700	1000 - 1400
Salt	4500 - 5500	2500 - 3100
Anhydrites	4000 - 5500	2200 - 3100
Limestones	3500 - 6000	2000 - 3300
Dolomites	3500 - 6500	1900 - 3600
Granite	4500 - 6000	2500 - 3300
Basalt	5000 - 6000	2800 - 2400
Gneiss	4400 - 5200	2700 - 3200



Fluids are not rigid at all.
Porosity and saturation
Clay content
Compaction and cementation

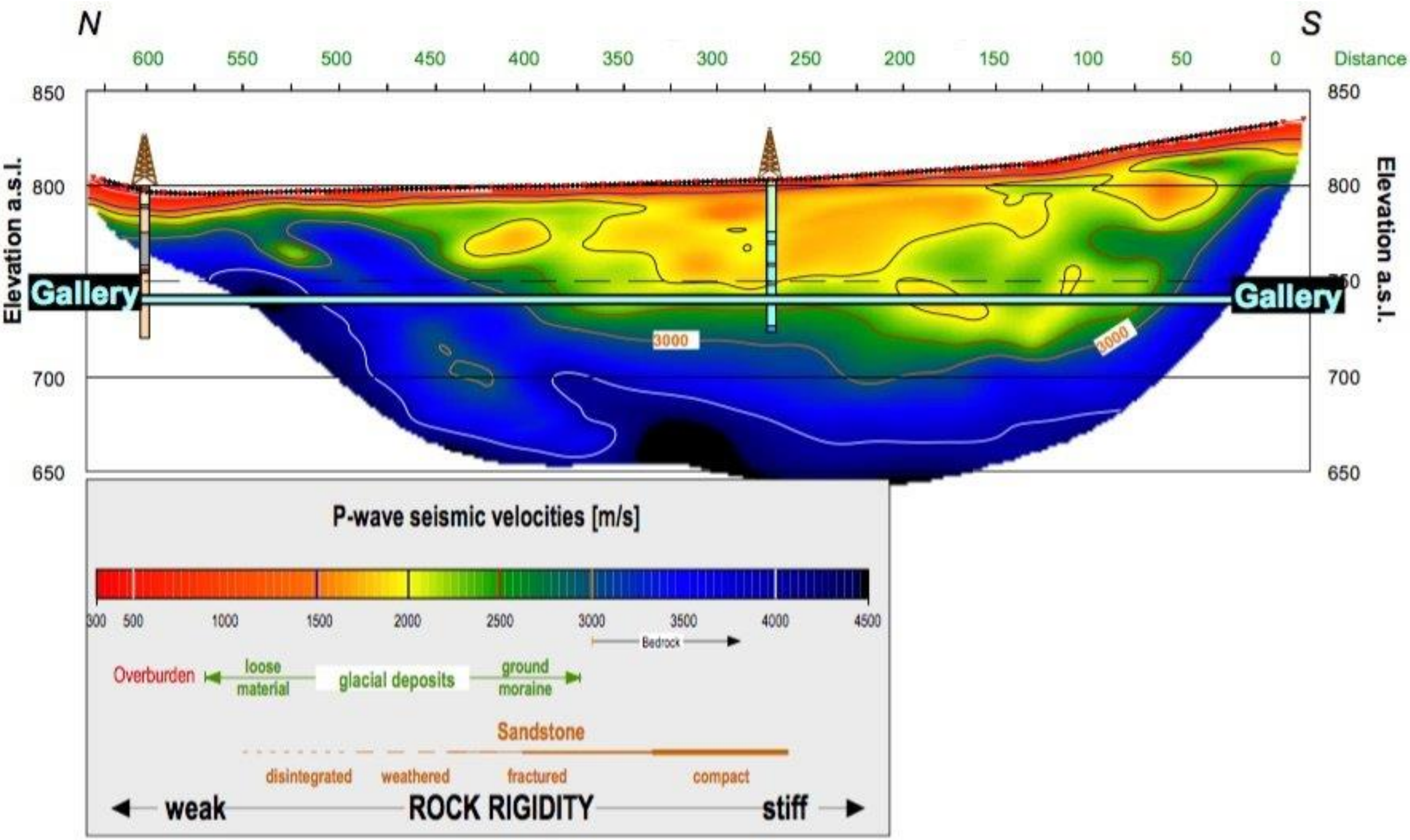
Velocity vs. depth



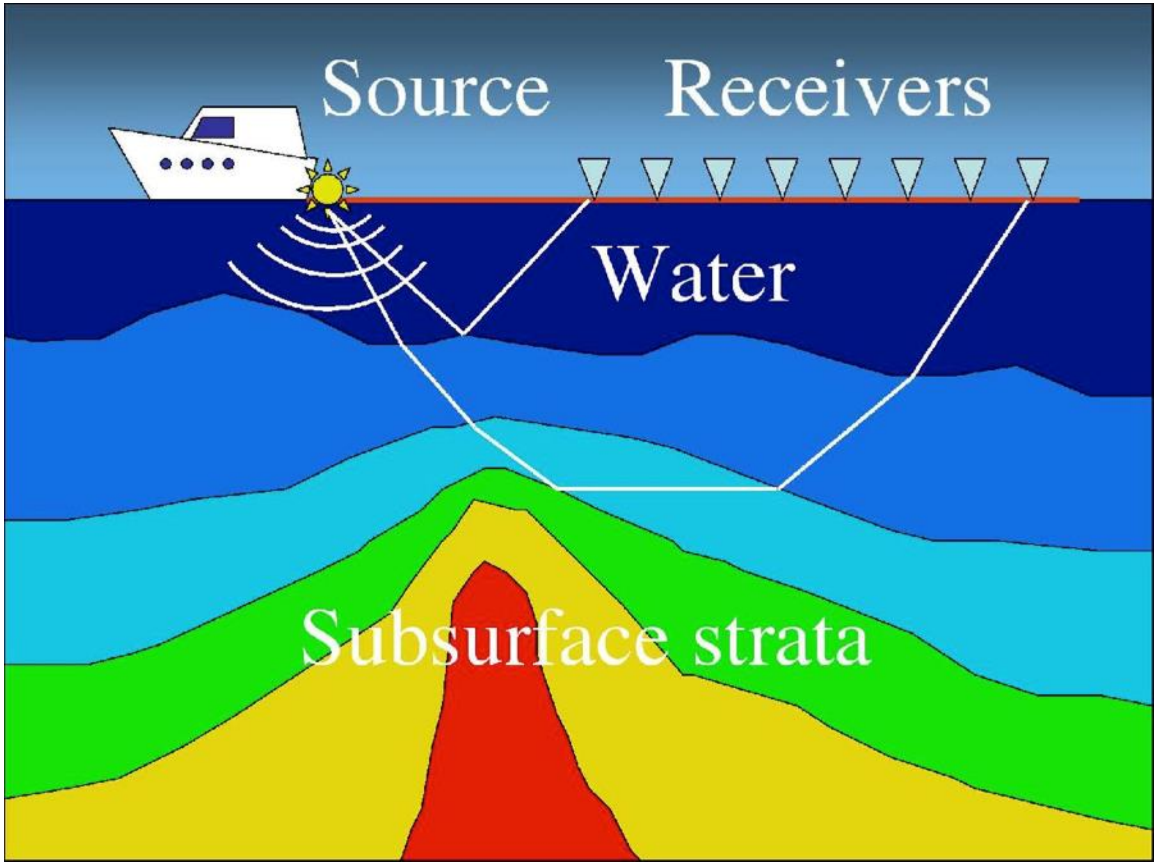
$$v_p = \sqrt{\frac{K + 4/3\mu}{\rho}}$$

Question: velocity increase or decrease with depth?

Velocity vs. depth

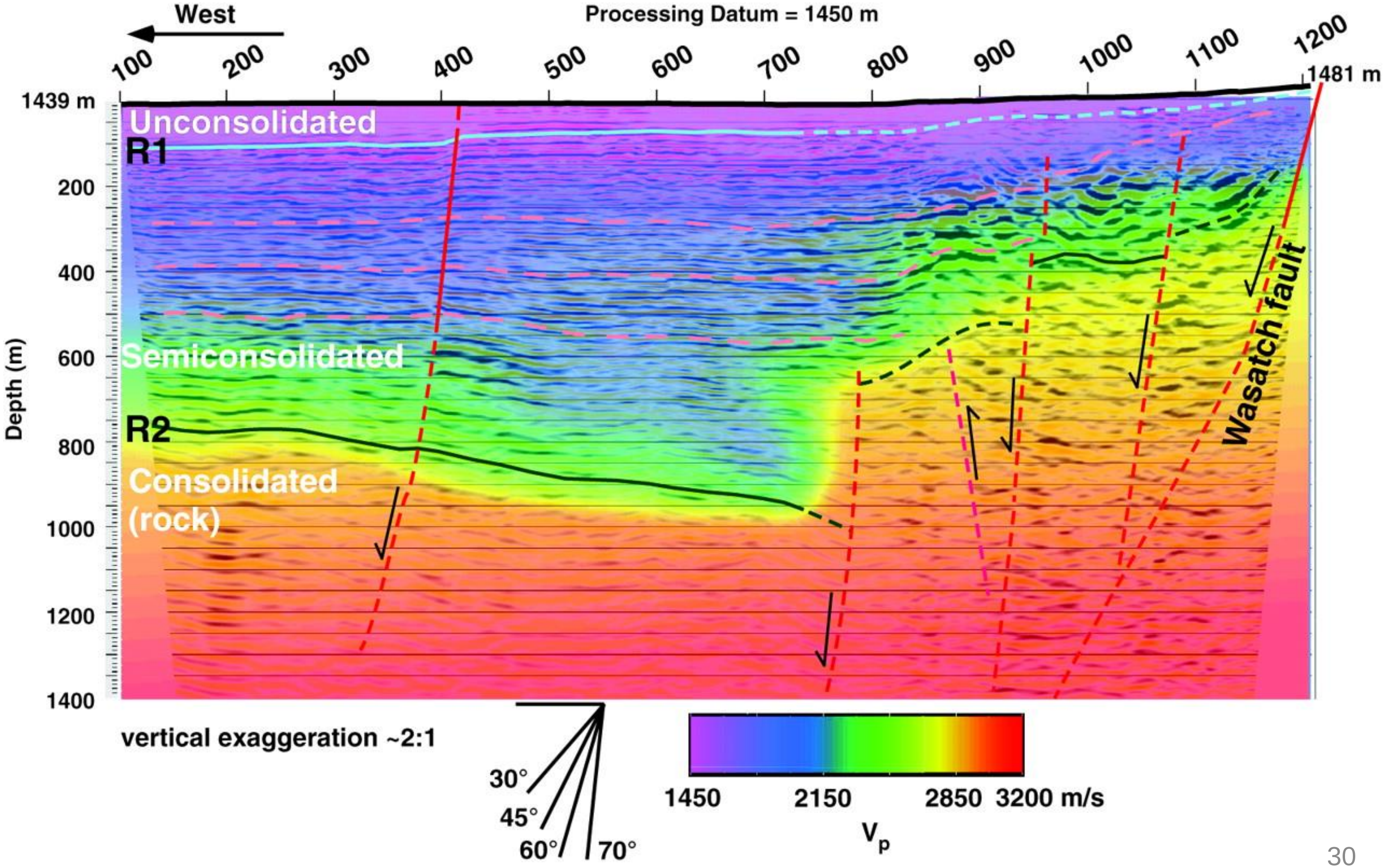


Seismic tomography

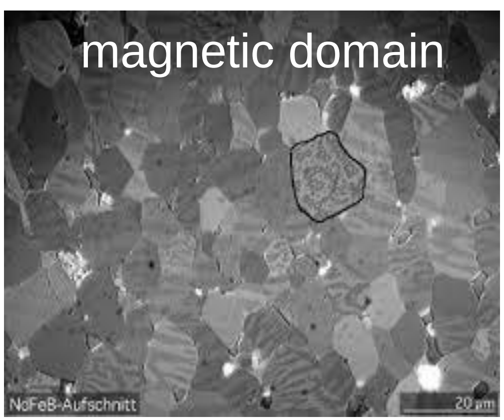


- velocity = distance / travel time
- many ray paths from multiple pairs of source-receiver

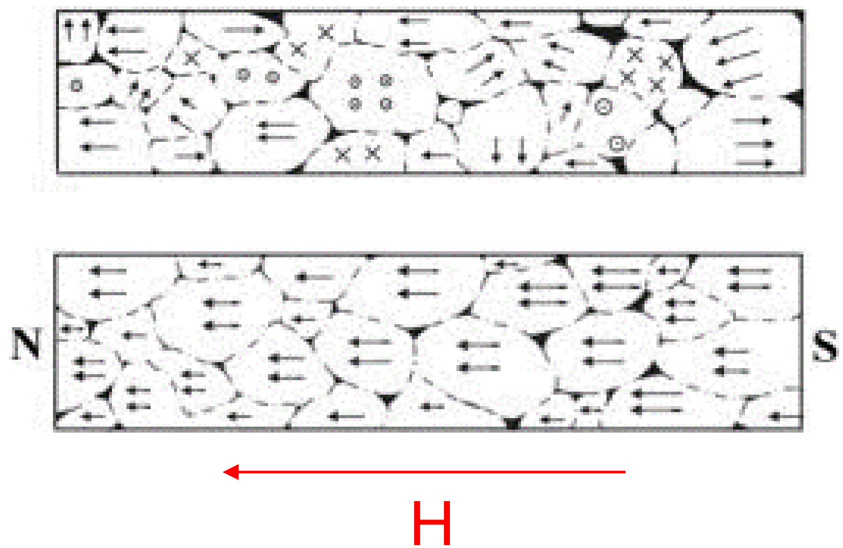
Seismic tomography



Magnetic susceptibility

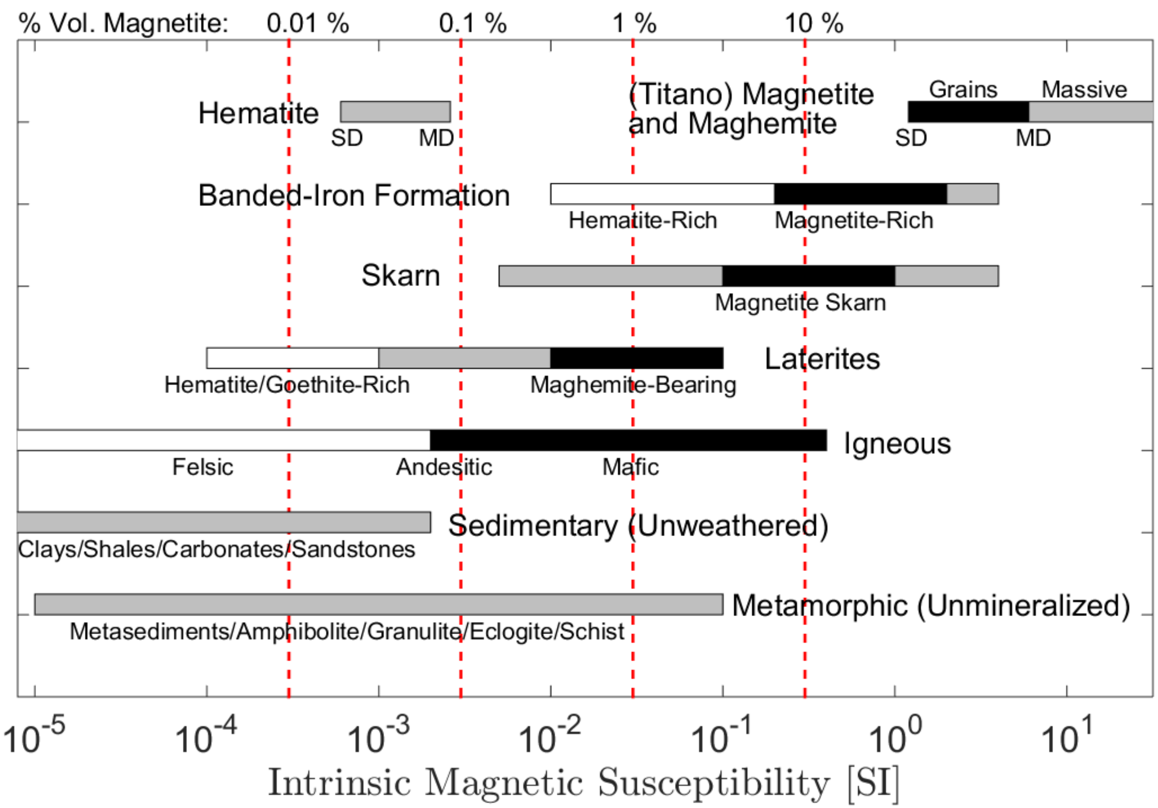


Magnetization



$$\vec{M} = \kappa \vec{H}$$

Susceptibilities of common rocks



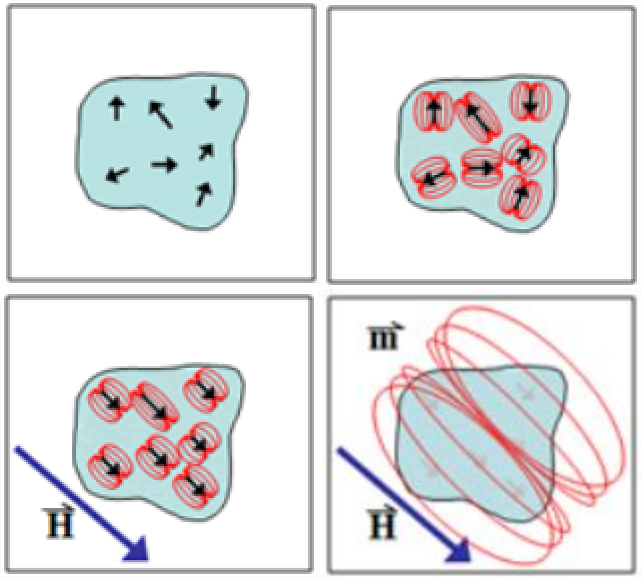
igneous/metamorphic > sedimentary

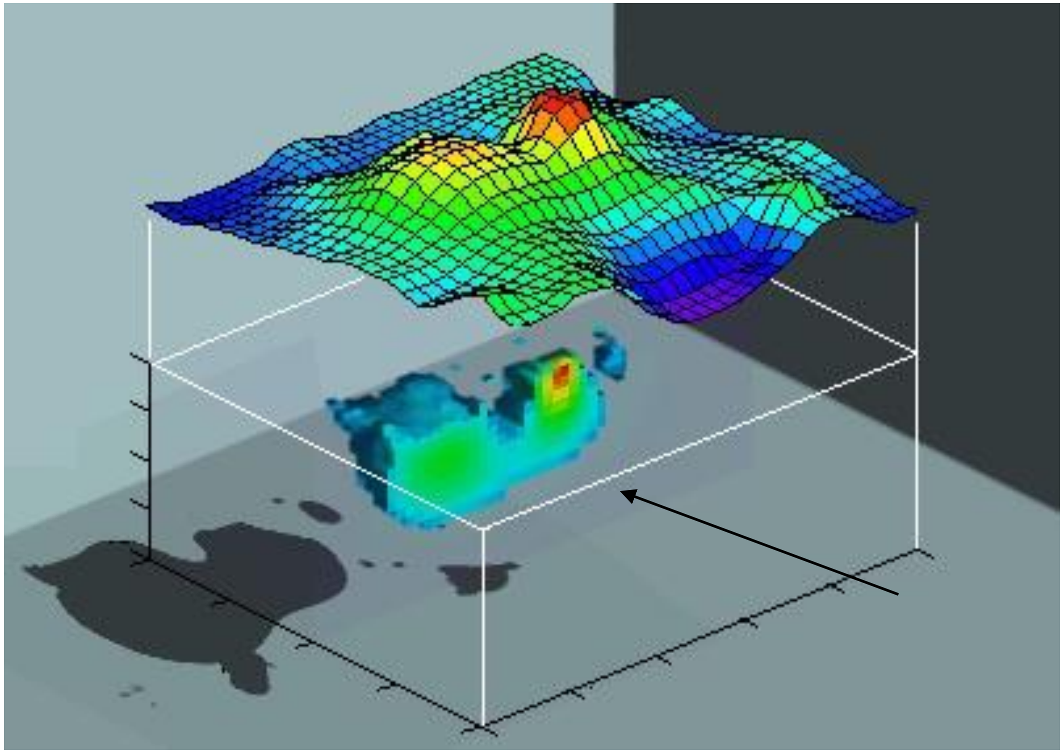
mafic > felsic

mineralized > country rock

Mineral	Chemical formula
Magnetite	Fe_3O_4
Ilmenite	$FeTiO_3$
Hematite	Fe_2O_3
Maghemite	Fe_2O_3
Pyrite	FeS_2
Pyrrhotite	$Fe_{1-x}S(Fe_7S_8)$

Magnetic exploration

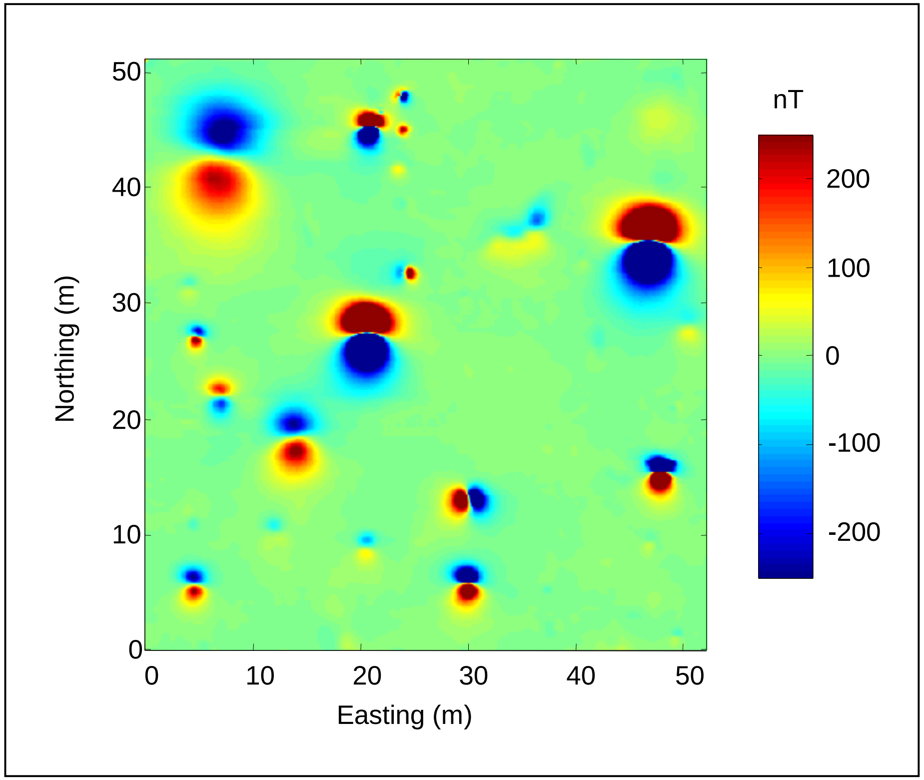




Mineralized rocks -> iron oxide/sulphide -> high susceptibility -> perturb local geo-magnetic field

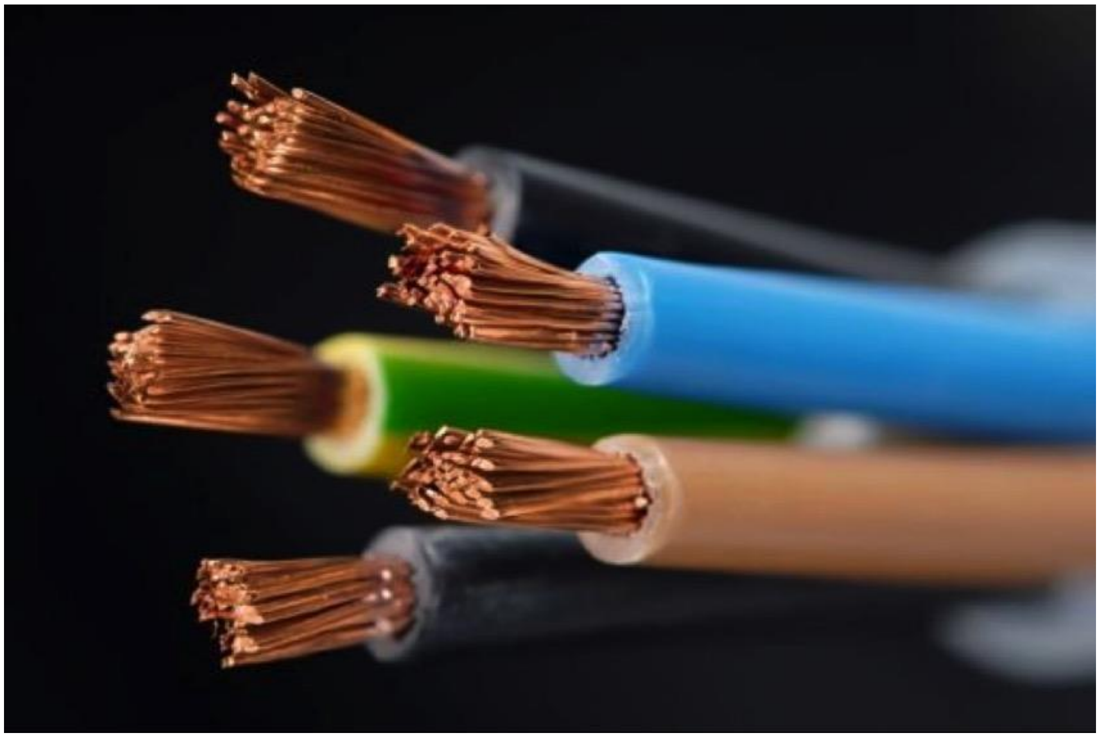
Magnetic exploration

TM4

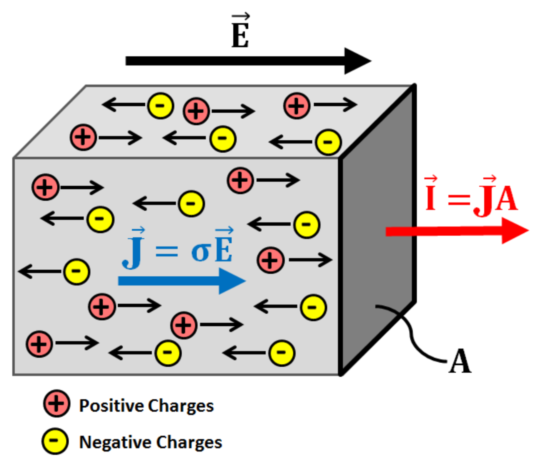


UXO’s -> iron/steel -> high susceptibility -> perturb local geo-magnetic field

Electrical conductivity



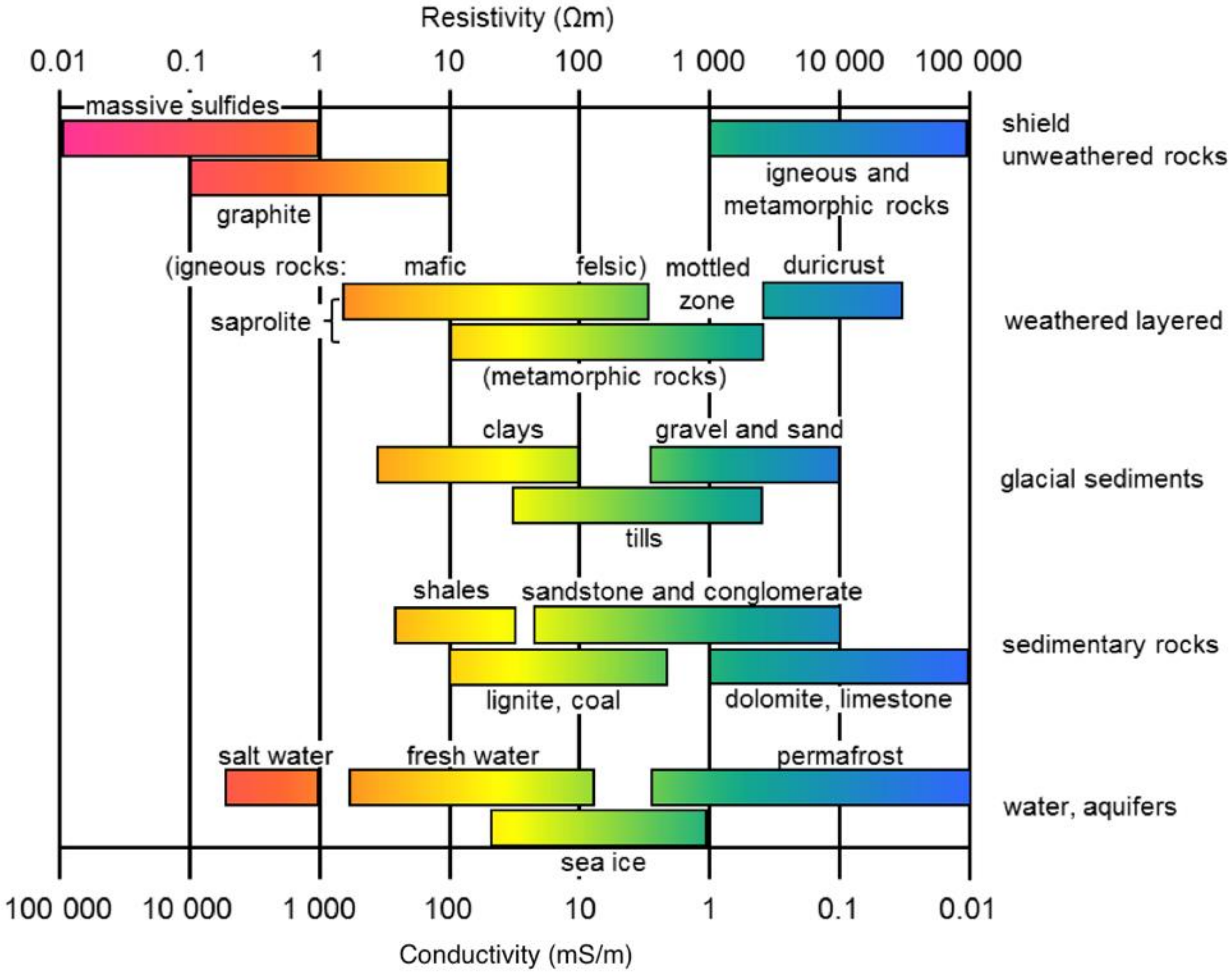
$$\vec{J} = \sigma \vec{E}$$

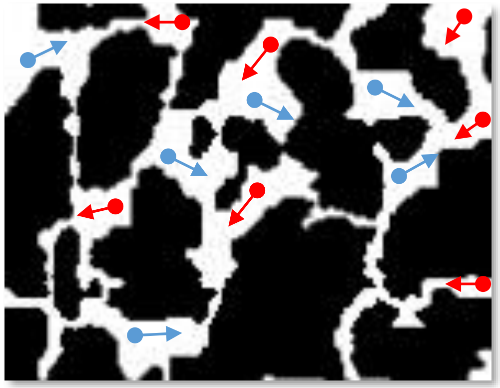


resistivity (Ωm):
reciprocal of conductivity (S/m)

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

Conductivity of common rocks



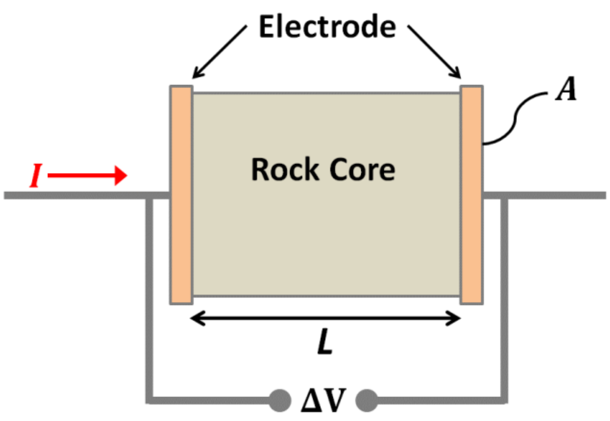


Concentration of charge carriers (electrons, ions)

Connectivity of pore-space network

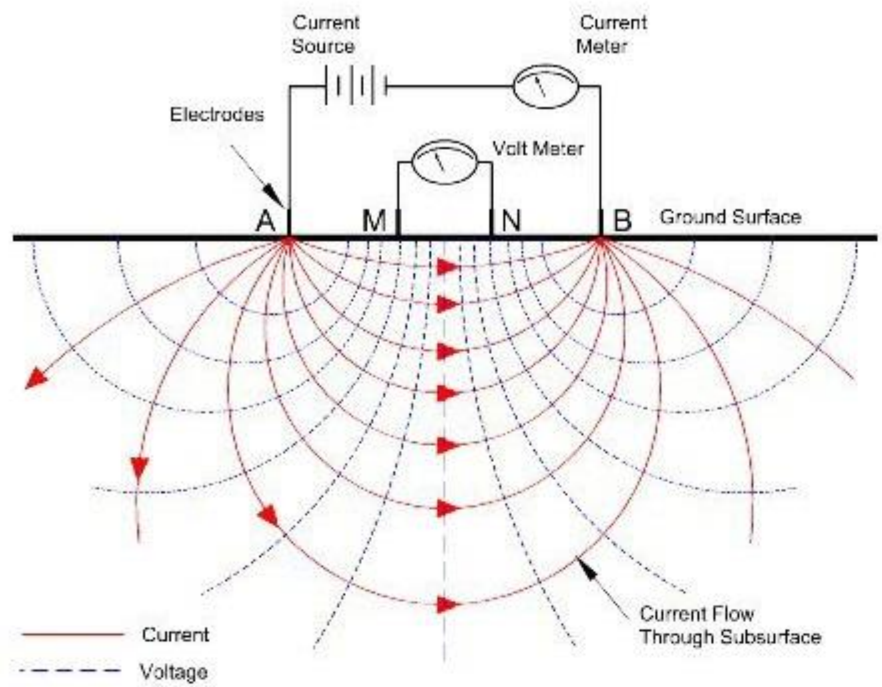
Conductivity measurements

Ohm's law



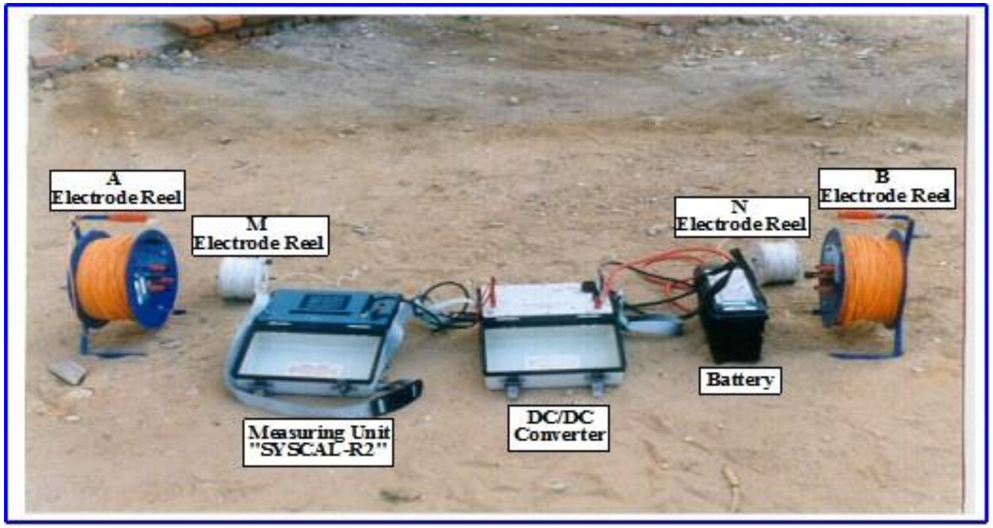
$$R = \frac{\Delta V}{I}$$

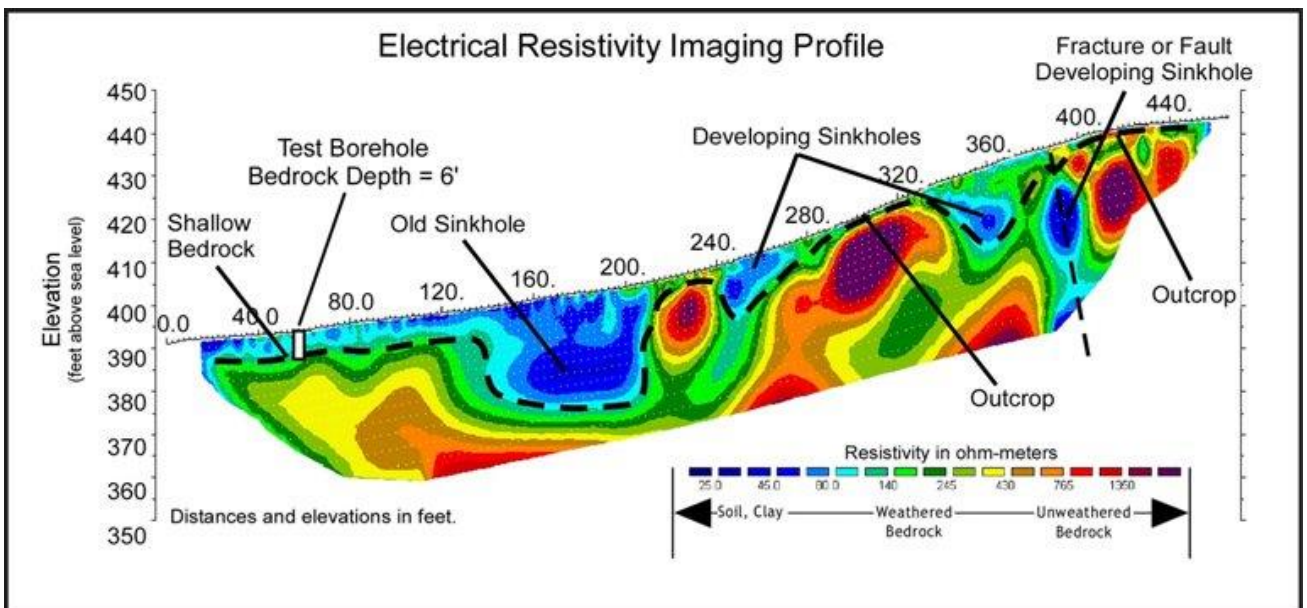
DC resistivity
(electric resistivity tomography)



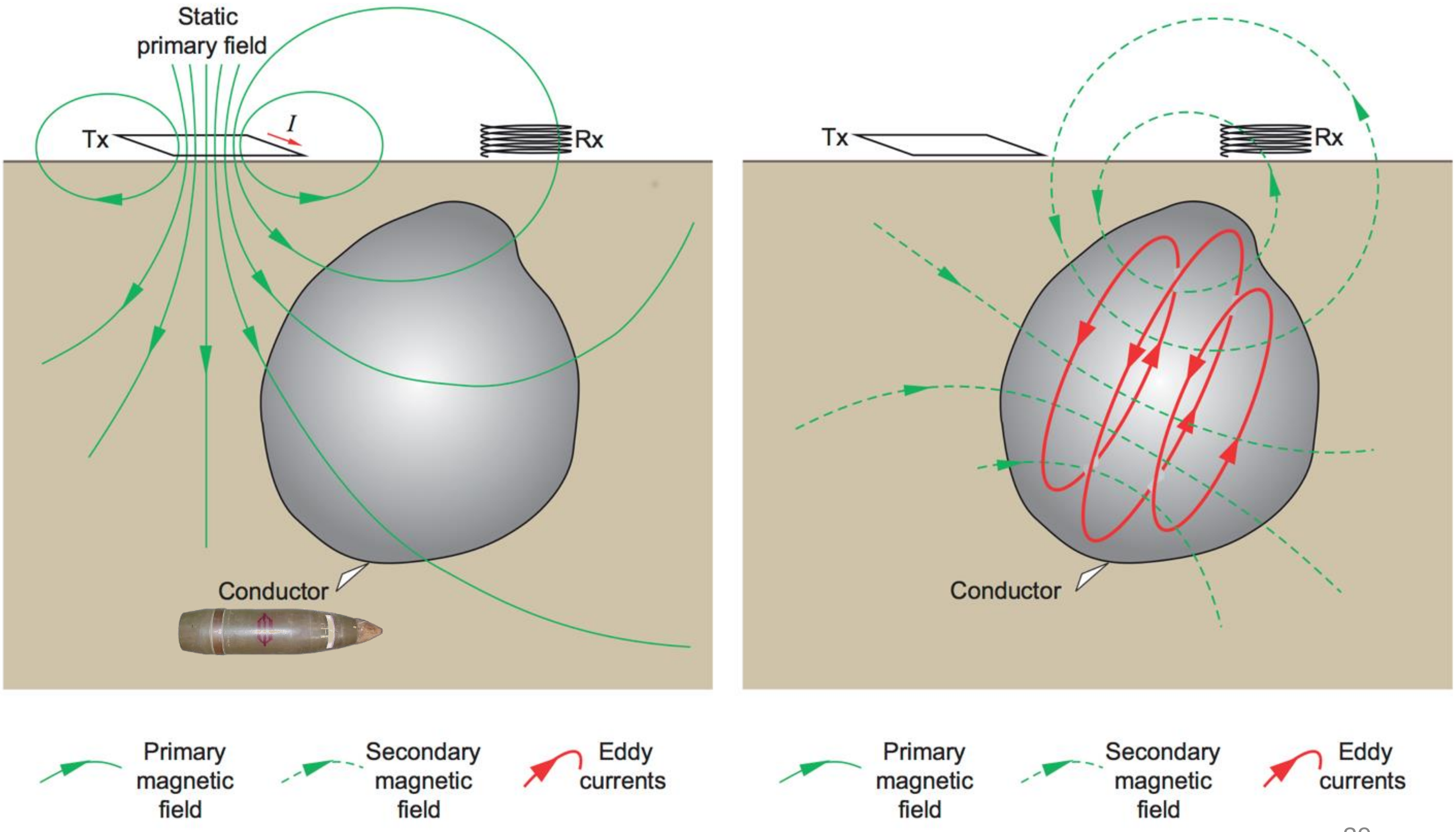
Question: how would the volt meter reading change if the electrodes are placed over a high conductivity body (e.g. a water-filled sinkhole)?

Electrical exploration

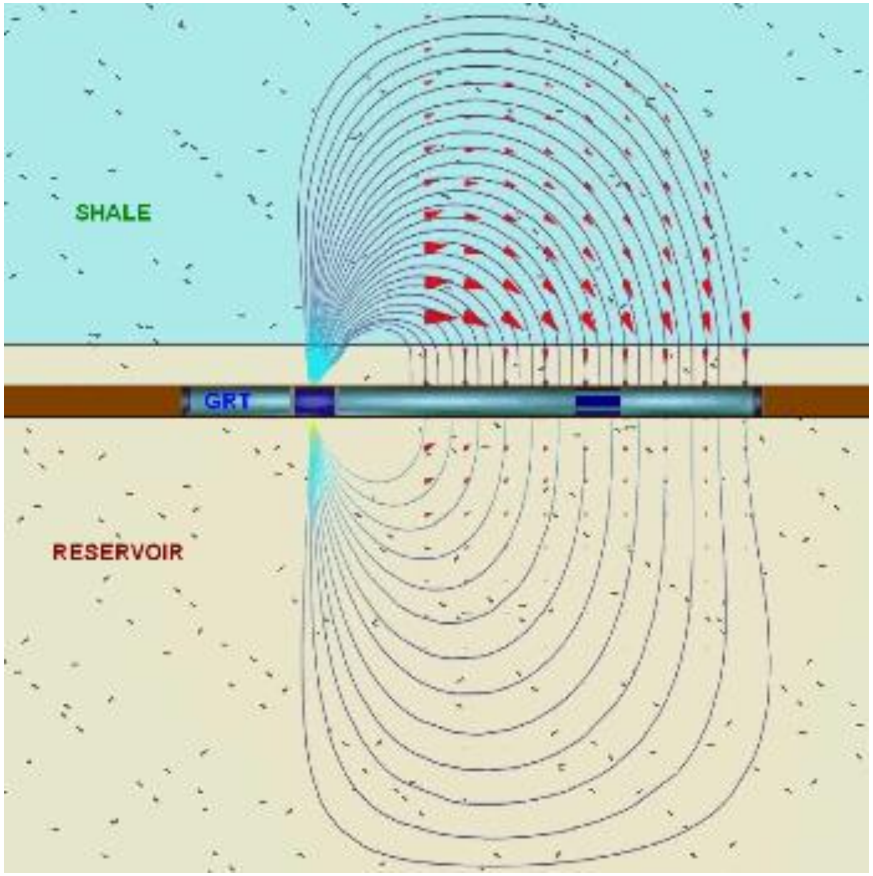


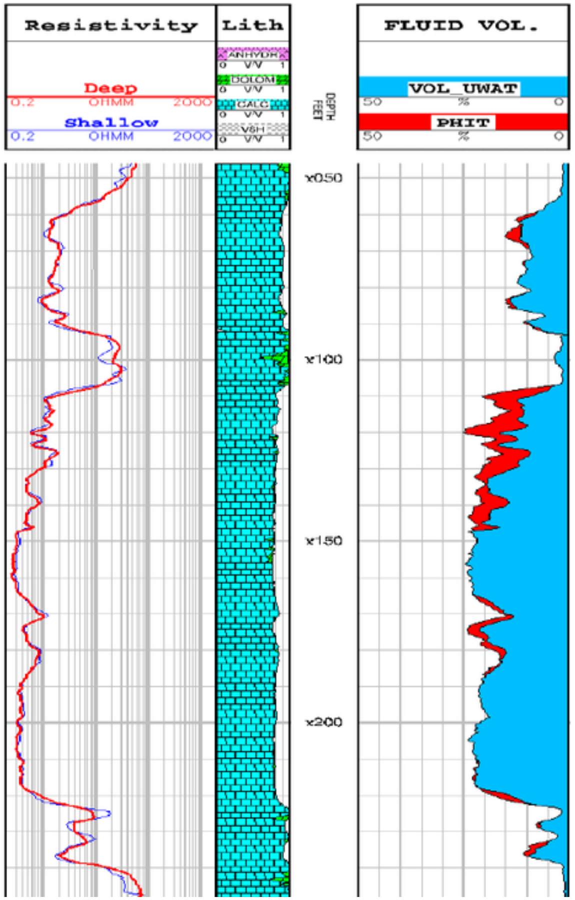


EM exploration

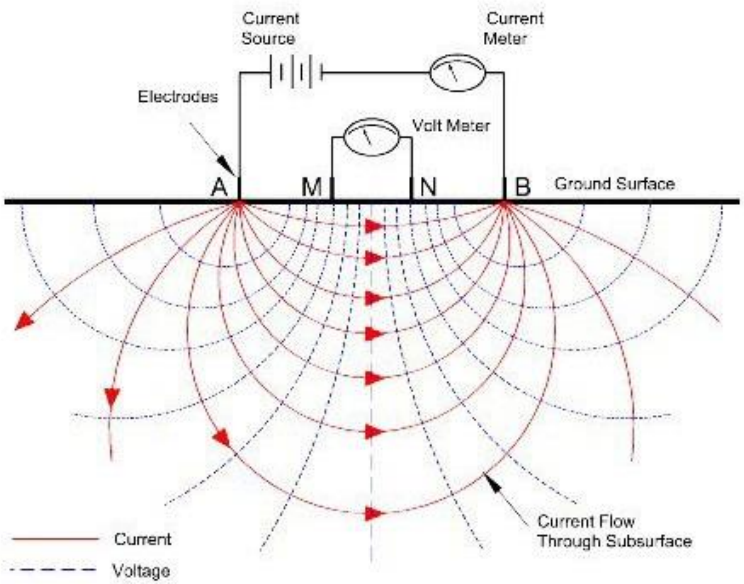


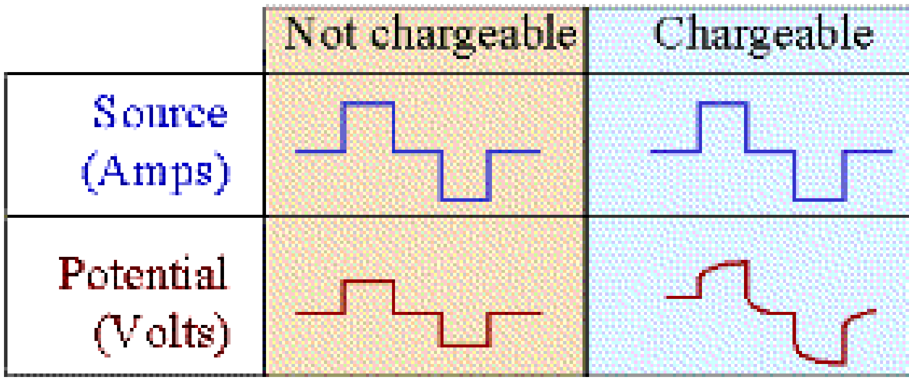
Resistivity logging





Chargeability

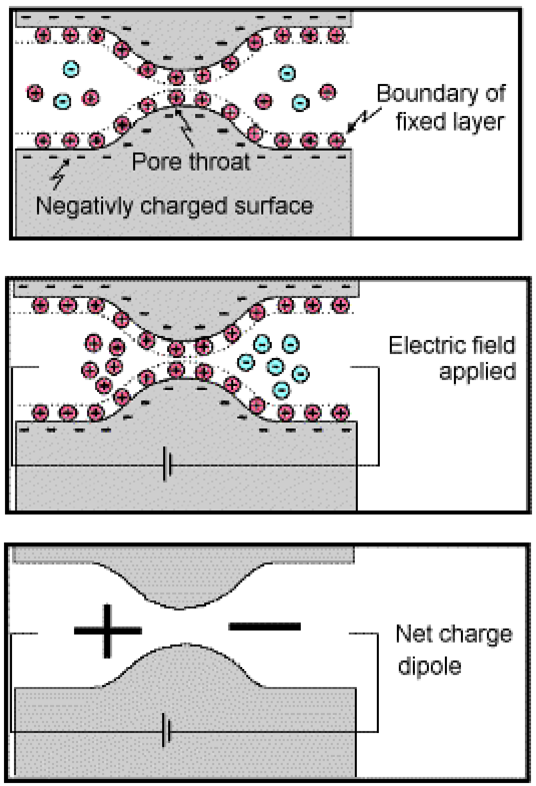




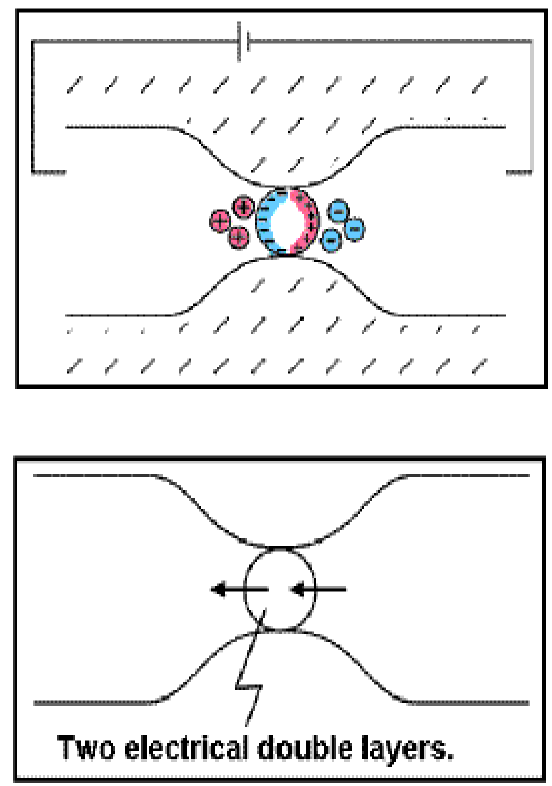
Induced polarization: sometimes the measured voltage does not change instantaneously after the source turns on and off.

Microscopic explanations

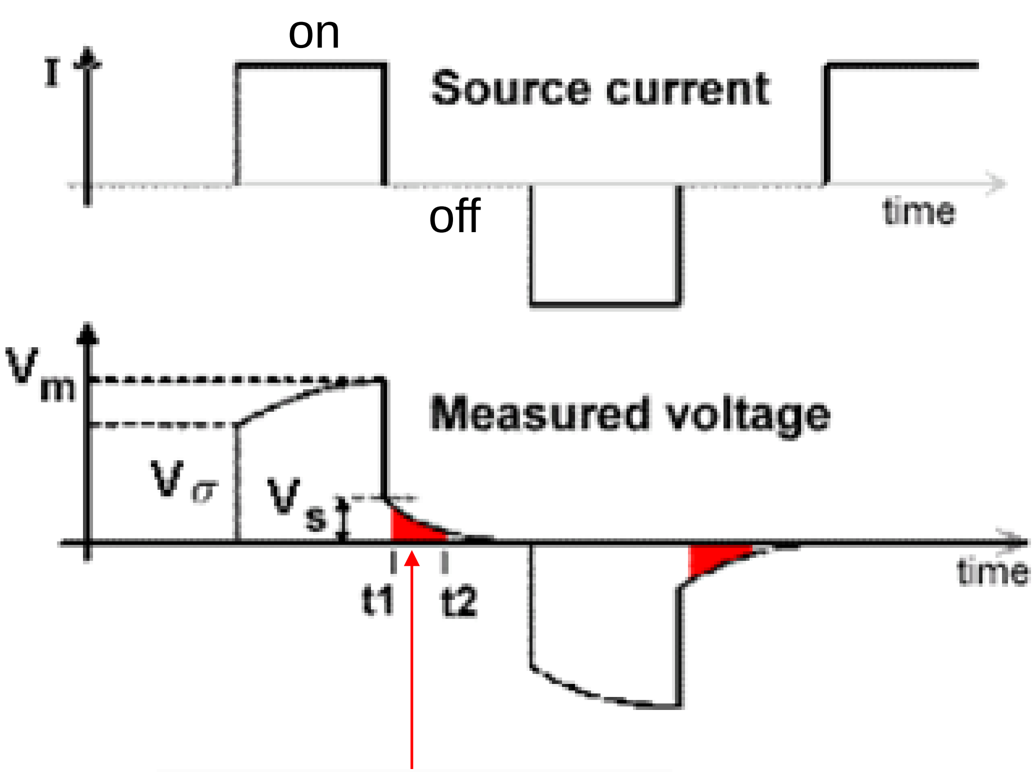
Membrane polarization



Electrode polarization



Effect of IP



$$V_{on}(t) = V_\sigma + V_s\left[1 - e^{-t/\tau}\right]$$

$$V_{off}(t) = V_s\, e^{-t/\tau}$$

Chargeability: relative contribution of the induced dipole moments to the total measured voltage

$$\eta = \frac{V_s}{V_m}$$

$$M = \frac{1}{V_m}\int_{t_1}^{t_2} V_{off}(t)\, dt$$

in unit of time

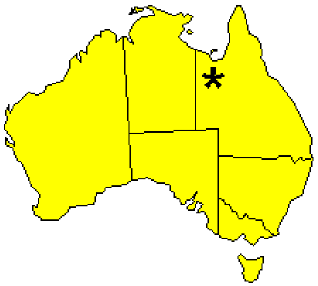
Chargeability of common rocks

Material type	Chargeability (msec)
ground water	0
alluvium	1-4
gravels	3-9
precambrian volcanics	8-20
precambrian gneisses	6-30
schists	5-20
sandstones	3-12
argilites	3-10
quartzites	5-12

Mineral Type	Chargeability (msec)
pyrite	13.4
chalcocite	13.2
copper	12.3
graphite	11.2
chalcopyrite	9.4
bornite	6.3
galena	3.7
magnetite	2.2
malachite	0.2

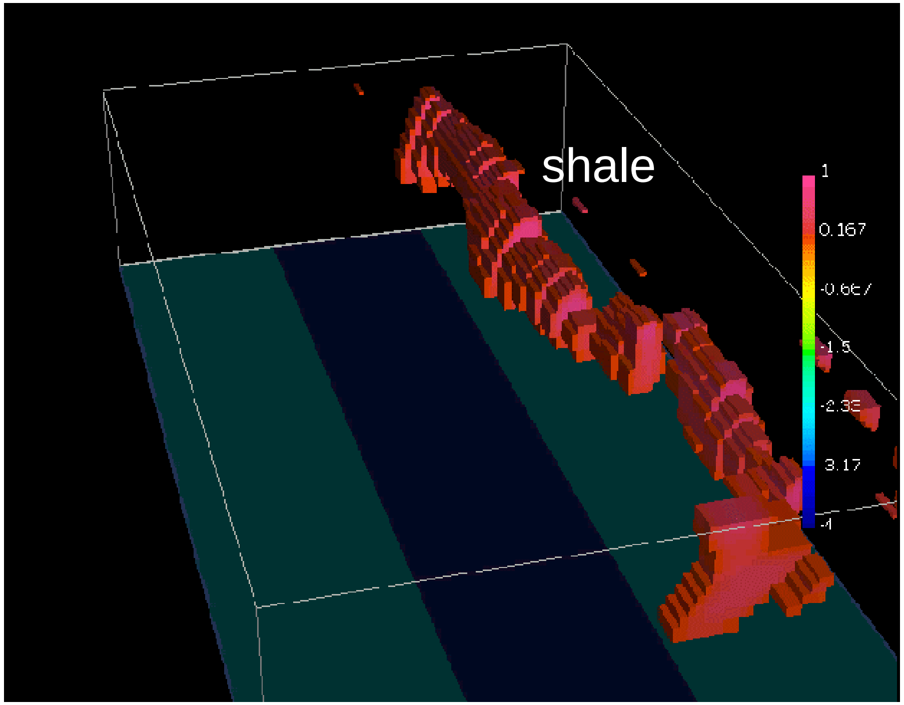
η = 10% is about 70 msec

DC and IP exploration

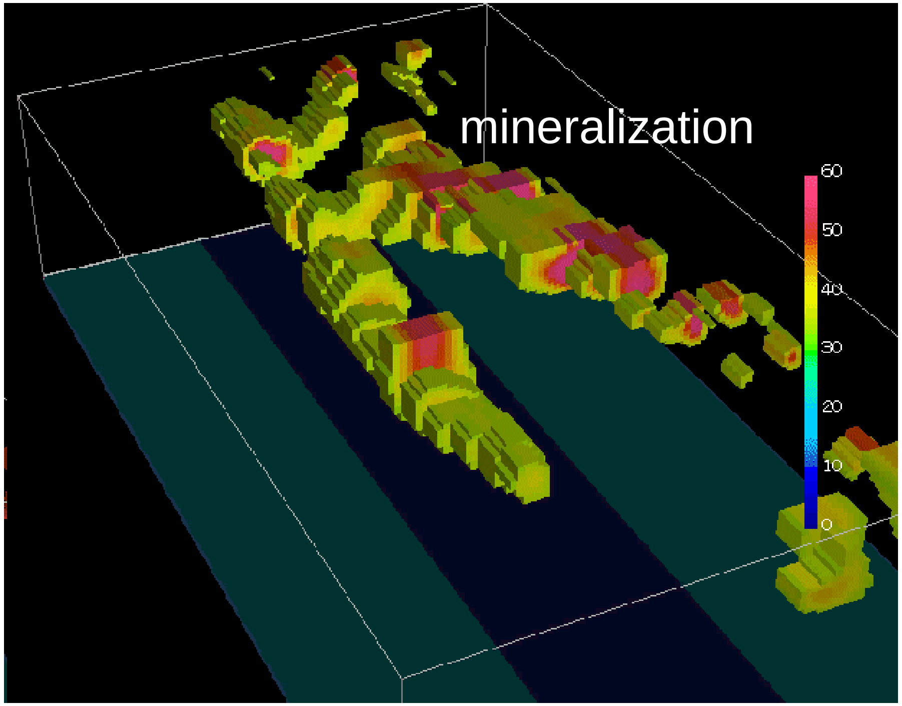


The “Cluny” copper/lead/zinc deposit

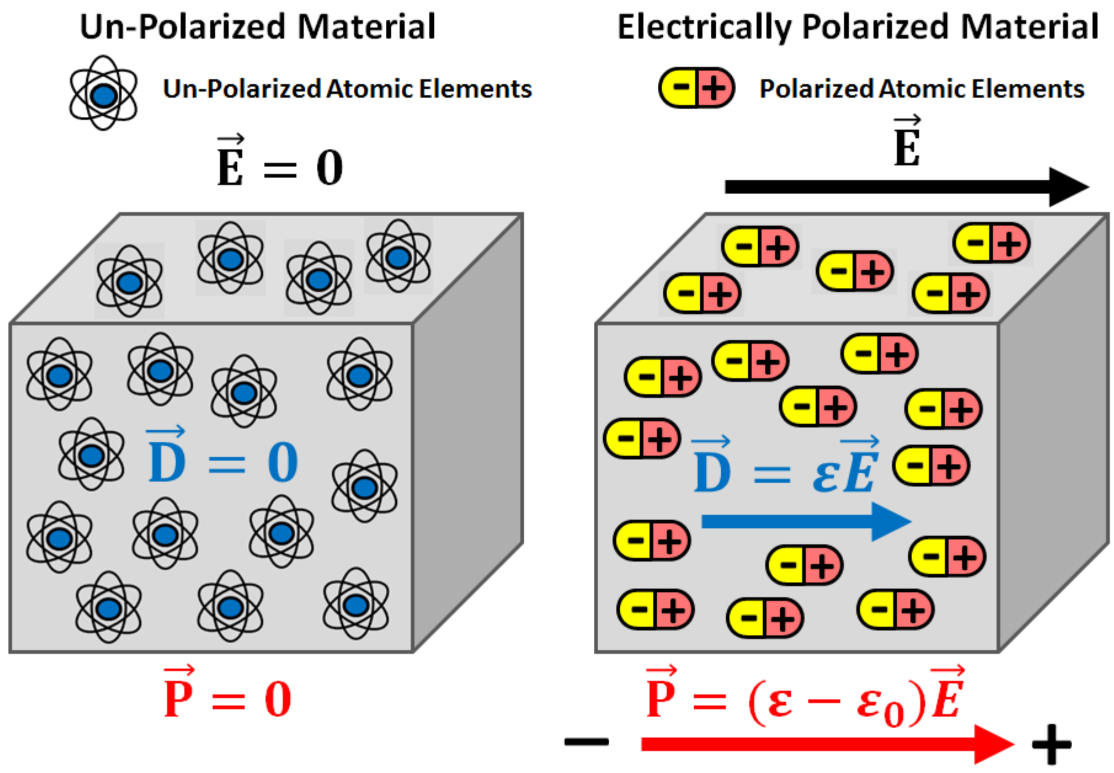
Volume rendered resistivity model



Volume rendered chargeability model



Dielectric permittivity



Compare: galvanic current $\vec{J} = \sigma\vec{E}$ and displacement current $\vec{D} = \varepsilon\vec{E}$

Vacuum (free space) has a non-zero permittivity $\varepsilon_0 = 8.8541878176 \times 10^{-12}$ F/m

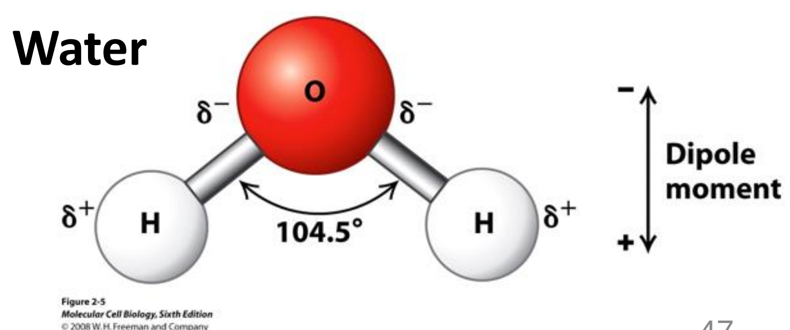
Relative Permittivity

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

Material	ε_r
Air	1
Fresh Water	80
Sea Water	80

Material	ε_r
Fresh Water Ice	3 - 4
Sea Water Ice	4 - 8
Snow	8 - 12
Permafrost	4 - 8

Material	ε_r
Shales	5 - 15
Sandstones (dry)	2 - 3
Sandstones (wet)	5 - 10
Limestones	4 - 8
Granite	4 - 6
Coal (dry)	3.5
Coal (wet)	8



At high frequency: GPR

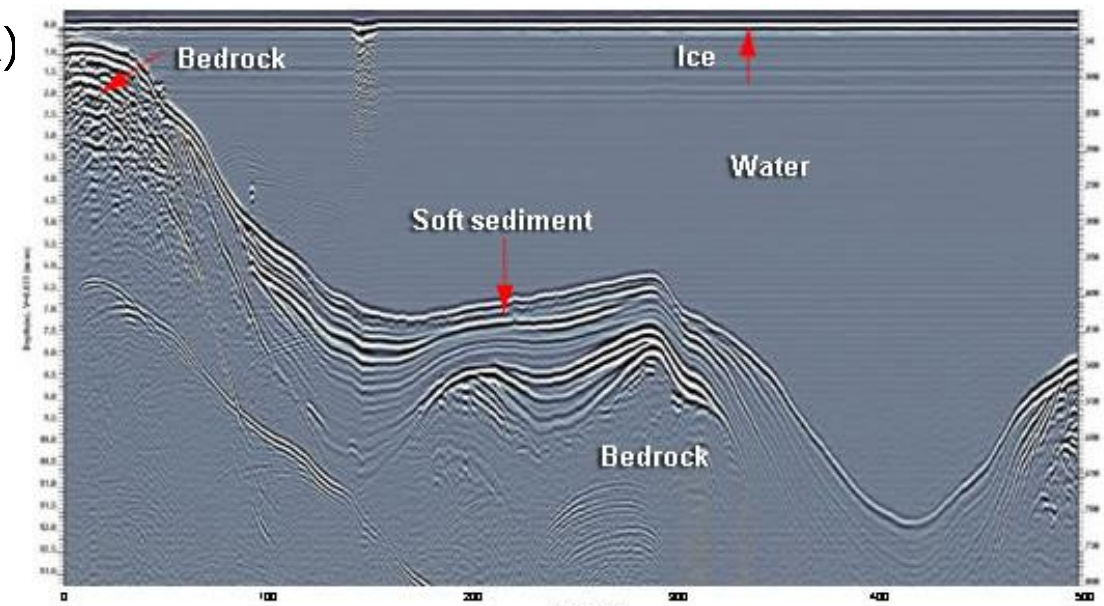
$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

$$\vec{J} = \sigma \vec{E}$$

$$\vec{D} = \varepsilon \vec{E}$$

ground penetrating radar (GPR)

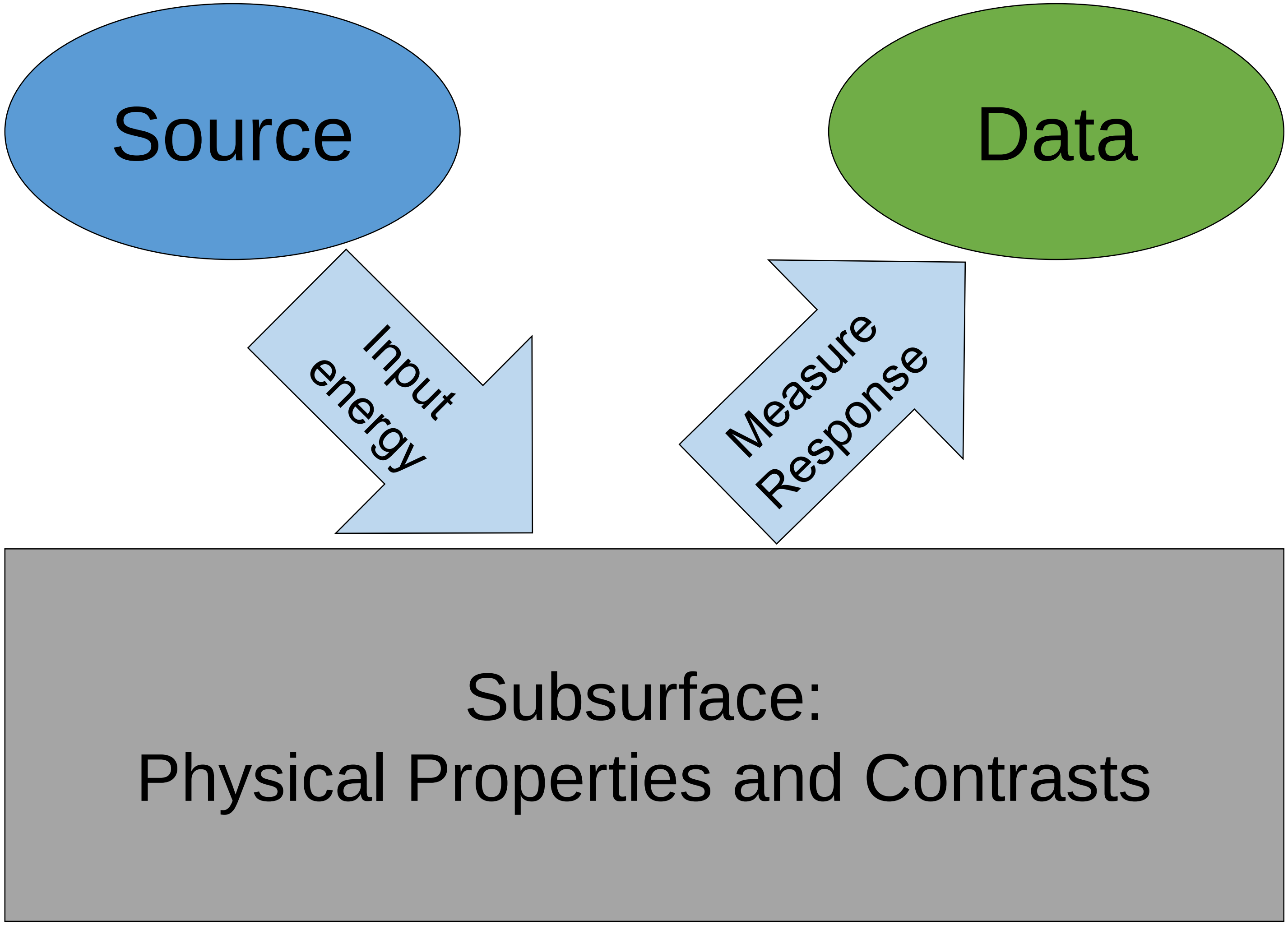
10 MHz to 2 GHz



pulseEKKO PRO 100 MHz cross-section showing lake-bathymetry and sub-bottom profiling.

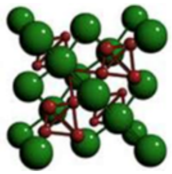
GPR wave velocity $v = \frac{c}{\sqrt{\varepsilon_r}}$

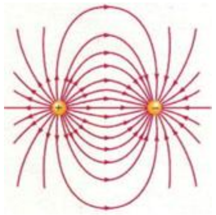
Solutions … Geophysics



Recap

- Characterize materials by physical properties:
  - Density
  - Magnetic susceptibility
  - Electrical conductivity
  - Chargeability
  - Electrical permittivity
  - Elastic moduli/velocity





Recap

- Each physical property has one or more survey methods:
  - Density → Gravity
  - Magnetic susceptibility → Magnetics
  - Electrical conductivity → DCR and EM
  - Chargeability → IP
  - Electrical permittivity → GPR
  - Elastic moduli/velocity → Seismology

Unit Activities

- **Labs: (Physical Properties)**
  - Monday, September 9th
  - Tuesday, September 10th

- **TBL:**
  - Wednesday, September 11th

- **Quiz:**
  - Wednesday, September 11th