Ground Penetrating Radar

- Begin a new section: Electromagnetics
- First EM survey: GPR (Ground Penetrating Radar)
- Physical Property: Dielectric constant
  Electrical Permittivity

Di-electric constant, conductivity, velocity

- Water has is extremely important
- **Attenuation** of radar signals is most affected by σ..

Table of relative dielectric permittivity (e_R), electrical conductivity (σ), and velocity.			
Material	e_R	σ (mSeimens/m)	V avg (m/ns)
Air	1	0	.3
Distilled water	**80**	**0.01**	0.033
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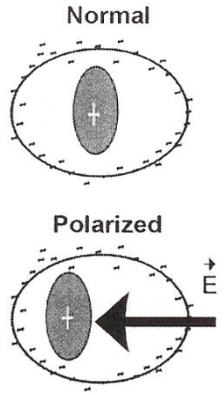
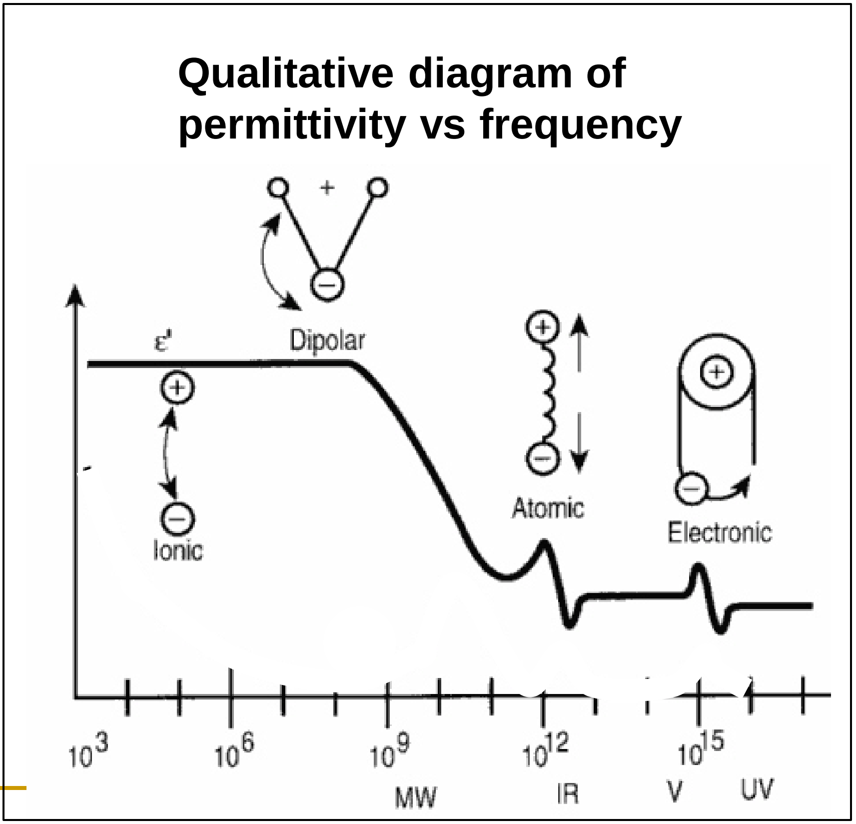
Saturated sand	20-30	0.1-1.0	0.06
Limestone	4-8	0.5-2.0	0.12
Shales	5-15	1-100	0.09
Silts	5-30	1-100	0.07
Clays	5-40	2- 1000	0.06
Granite	4-6	0.01-1.0	0.13
Dry salt	5-6	0.01-1.0	0.13
Ice	3-4	0.01	**0.16**

Dielectric permittivity, ε



- See GPG section 3.g.
- This physical property quantifies how easily material becomes polarized in the presence of an electric field.



Log frequency

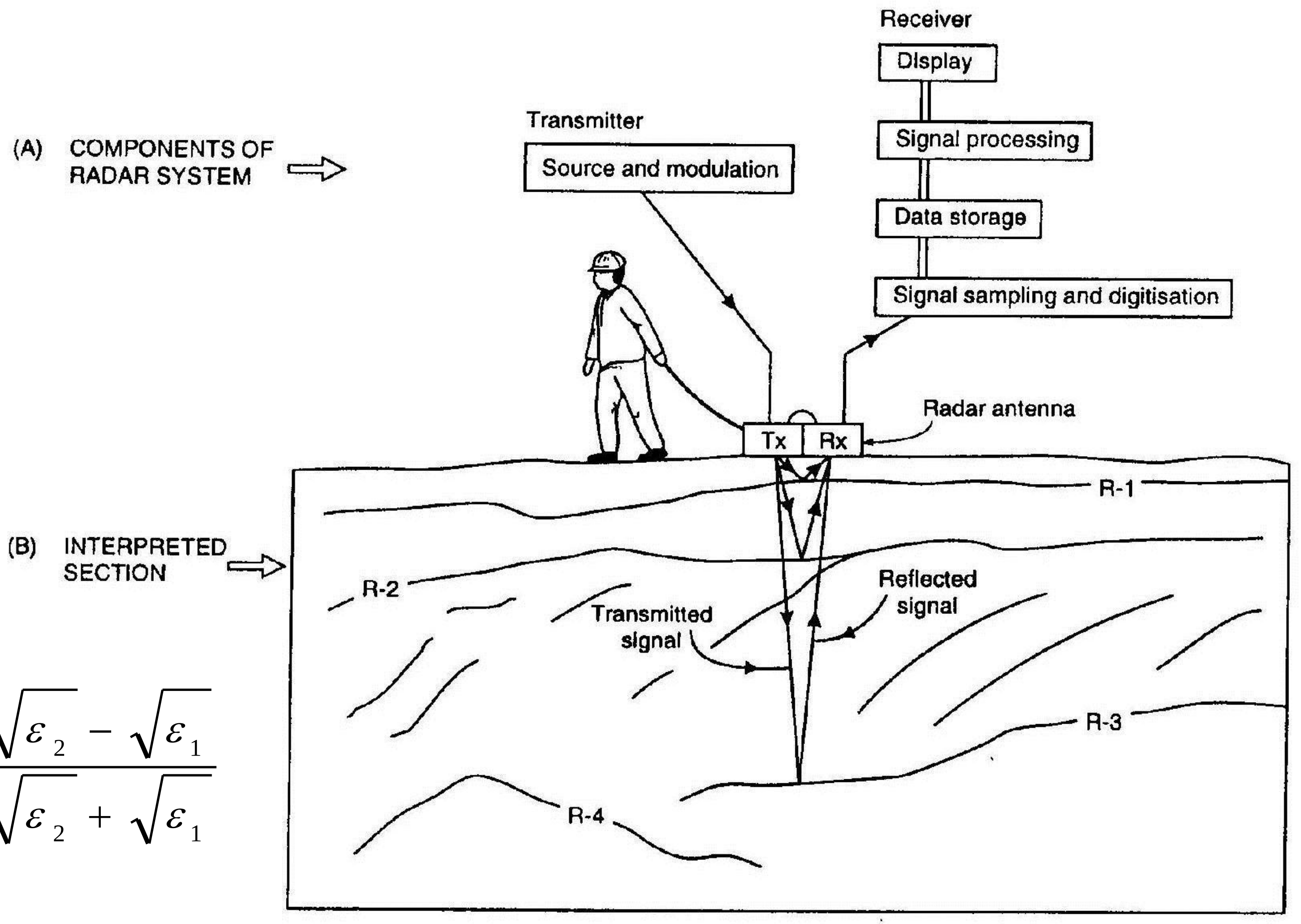
Relative permitivity

- Value of permittivity (ε) in freespace (ε_0) is 8.844E-12 *Farads/meter*

- *Relative permittivity* $\varepsilon_r = \varepsilon/\varepsilon_0$

- Where ε is the permittivity of the geologic material

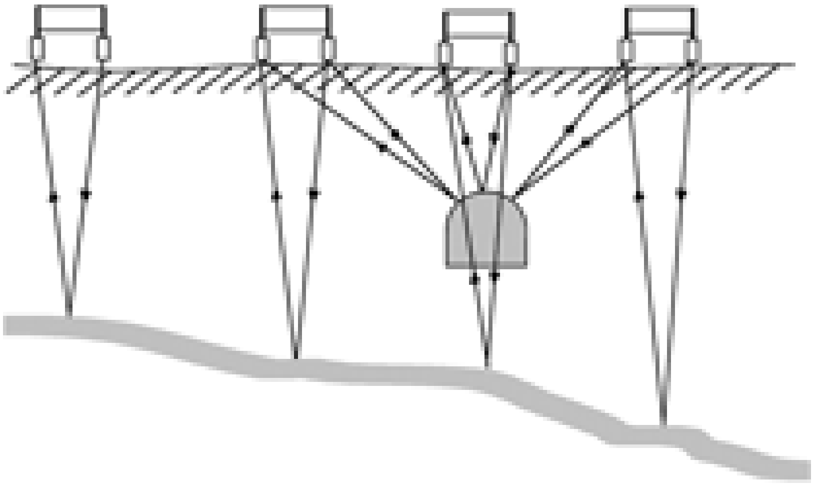
GPR Ground Penetrating Radar

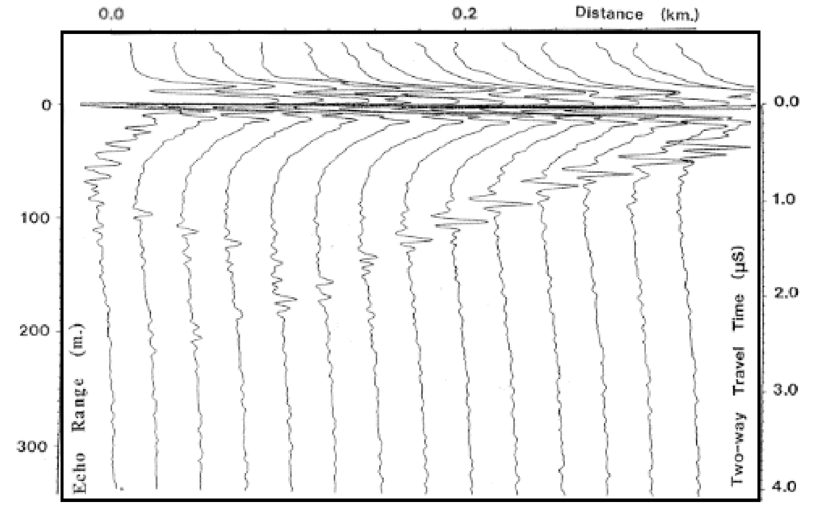


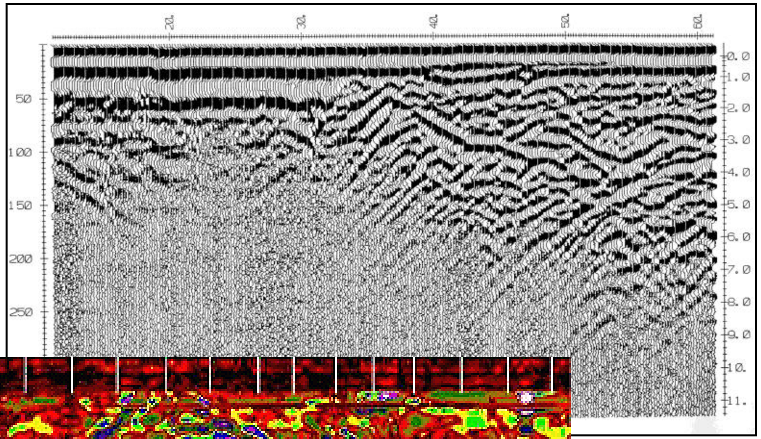
$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}}$$

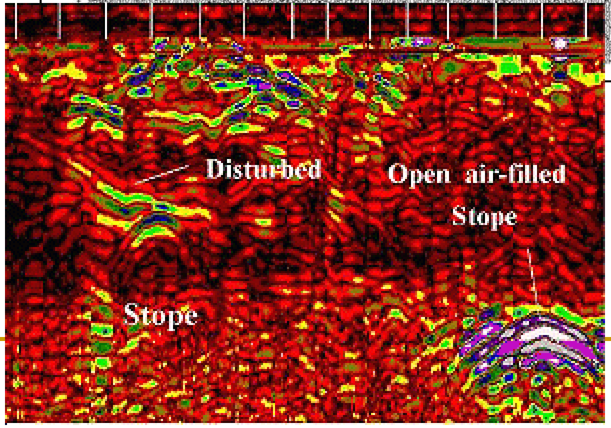
GPR data - echoes

- Essentially wiggle traces
  - Sometimes variable area
  - Sometimes as coloured bands



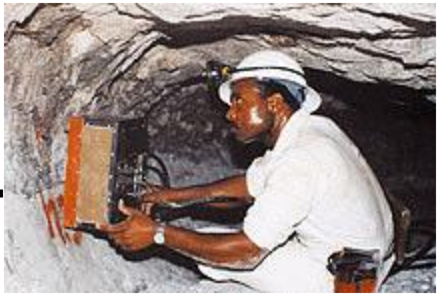


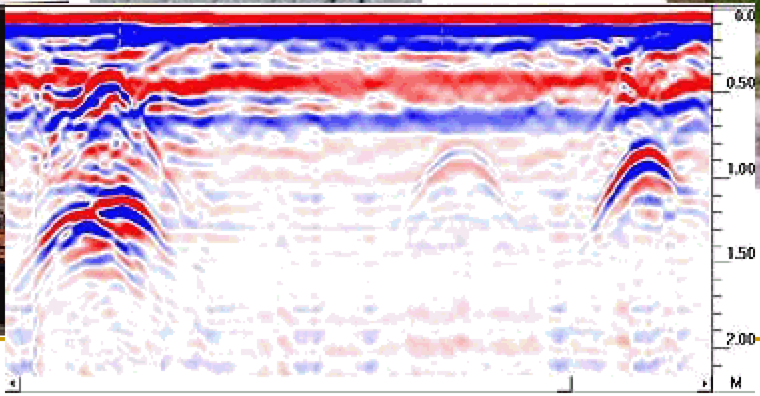




Examples of systems in use

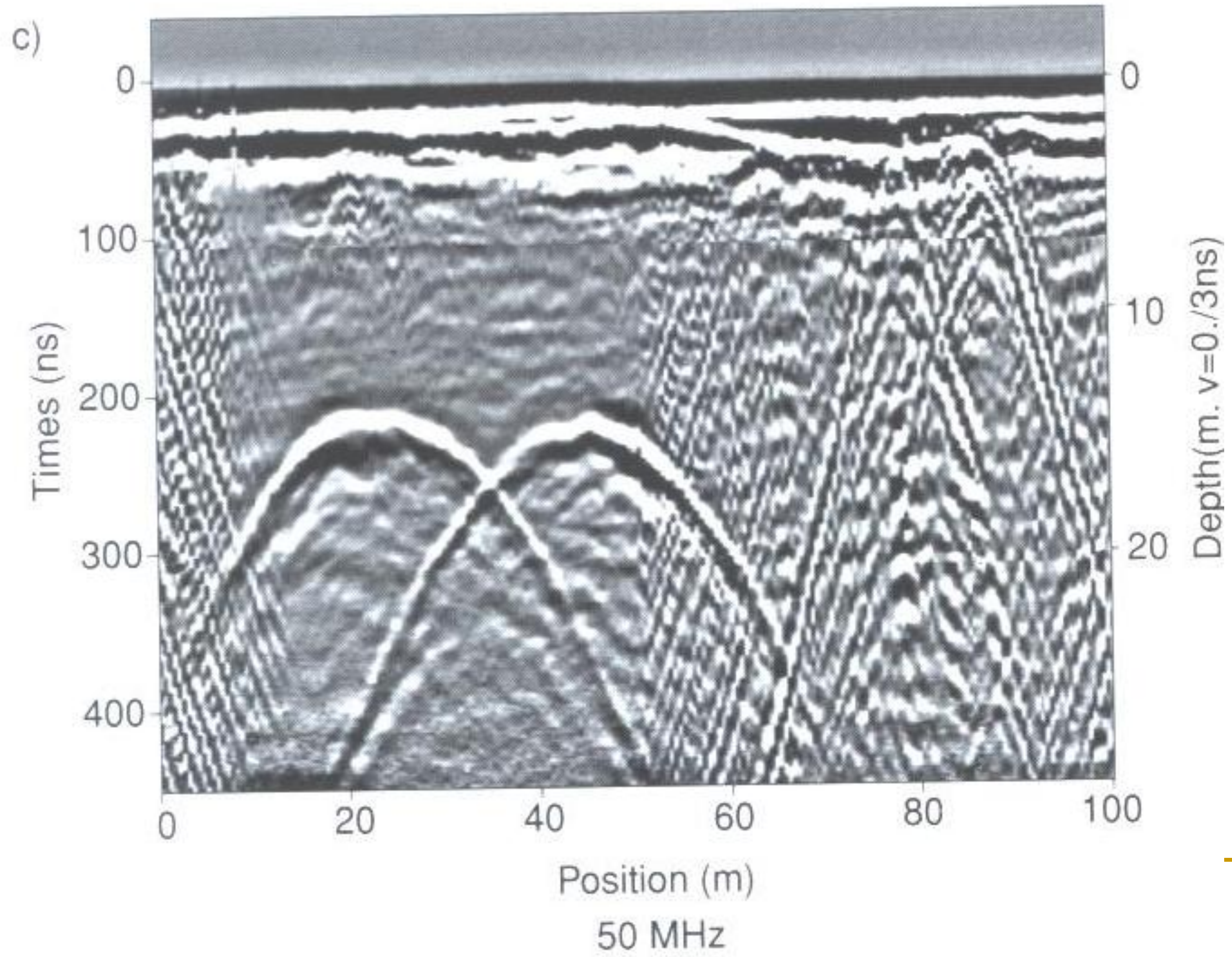
- Small scale, but expensive equipment.
- Limitations?





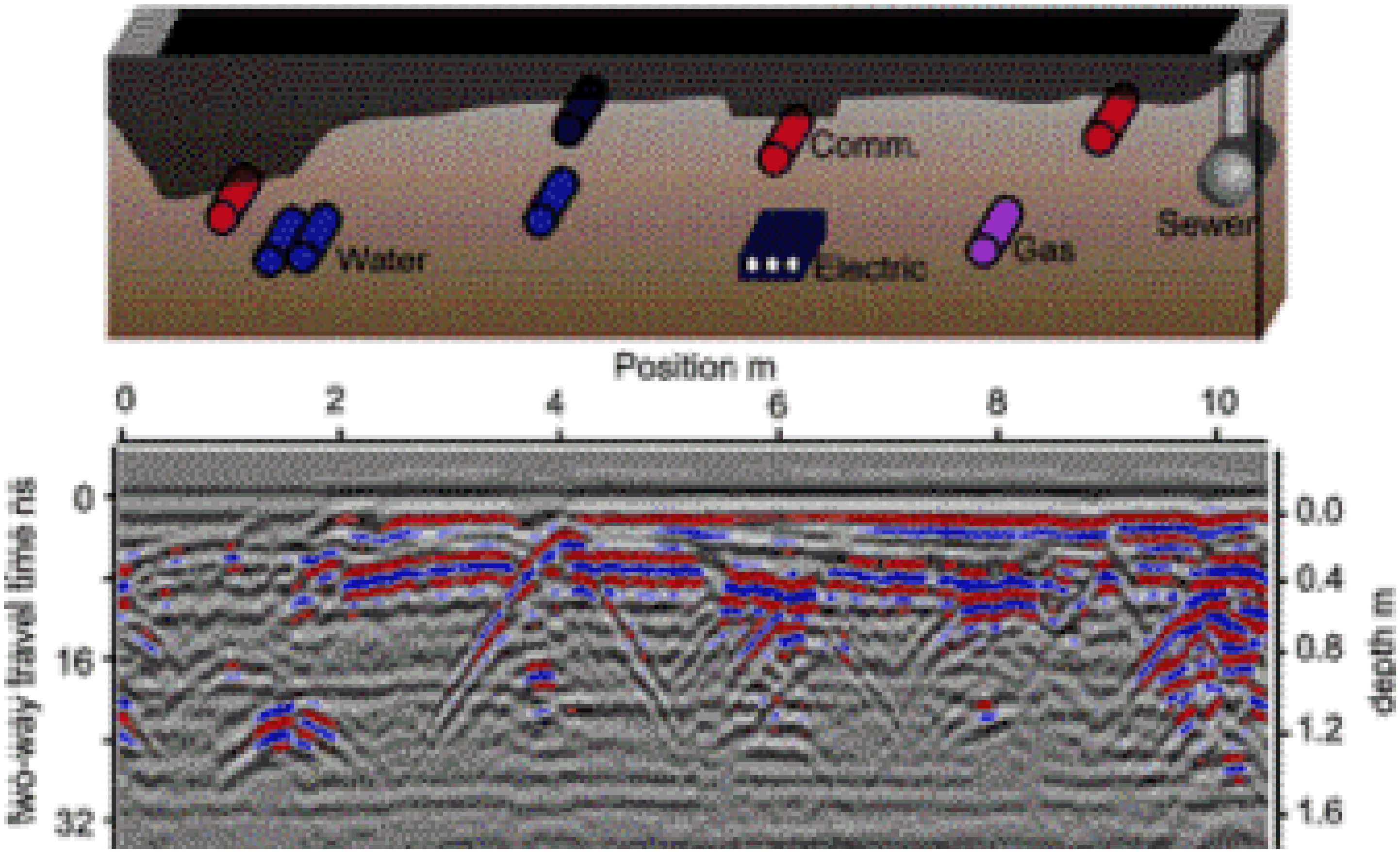
GPR Frequencies : 100 MHz,

Two underground tunnels,



Egs: Geotechnical applications

- Attenuation high in conductive ground (clays)
- Scattering from texture of materials produces “busy” images.



For GPR

- What is the source (i.e. input energy)?
- How does the energy travel in the earth?
- What are the data?

GPR sources

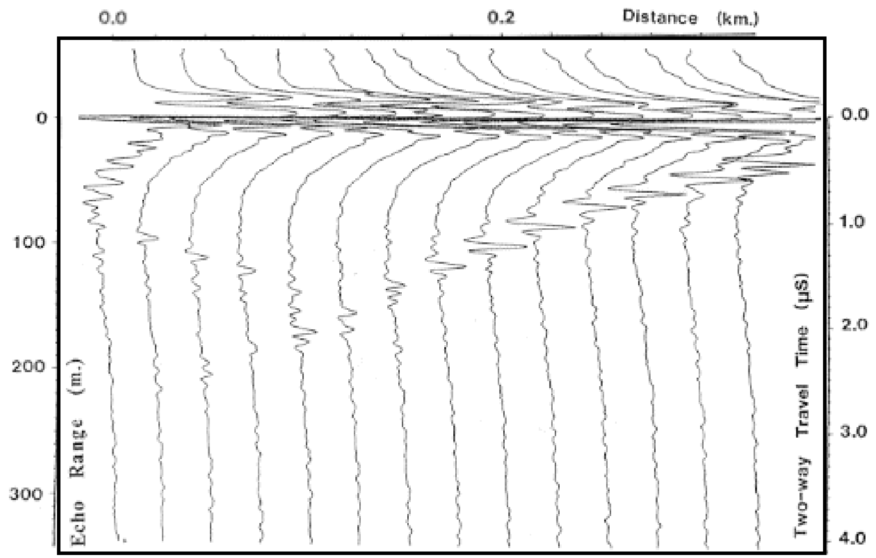
- Sources of energy are antennas that transmit a short pulse of energy

- The antenna is characterized
- by its frequency

- GPR frequencies typically
- range from 10^6 to 10^9 Hz

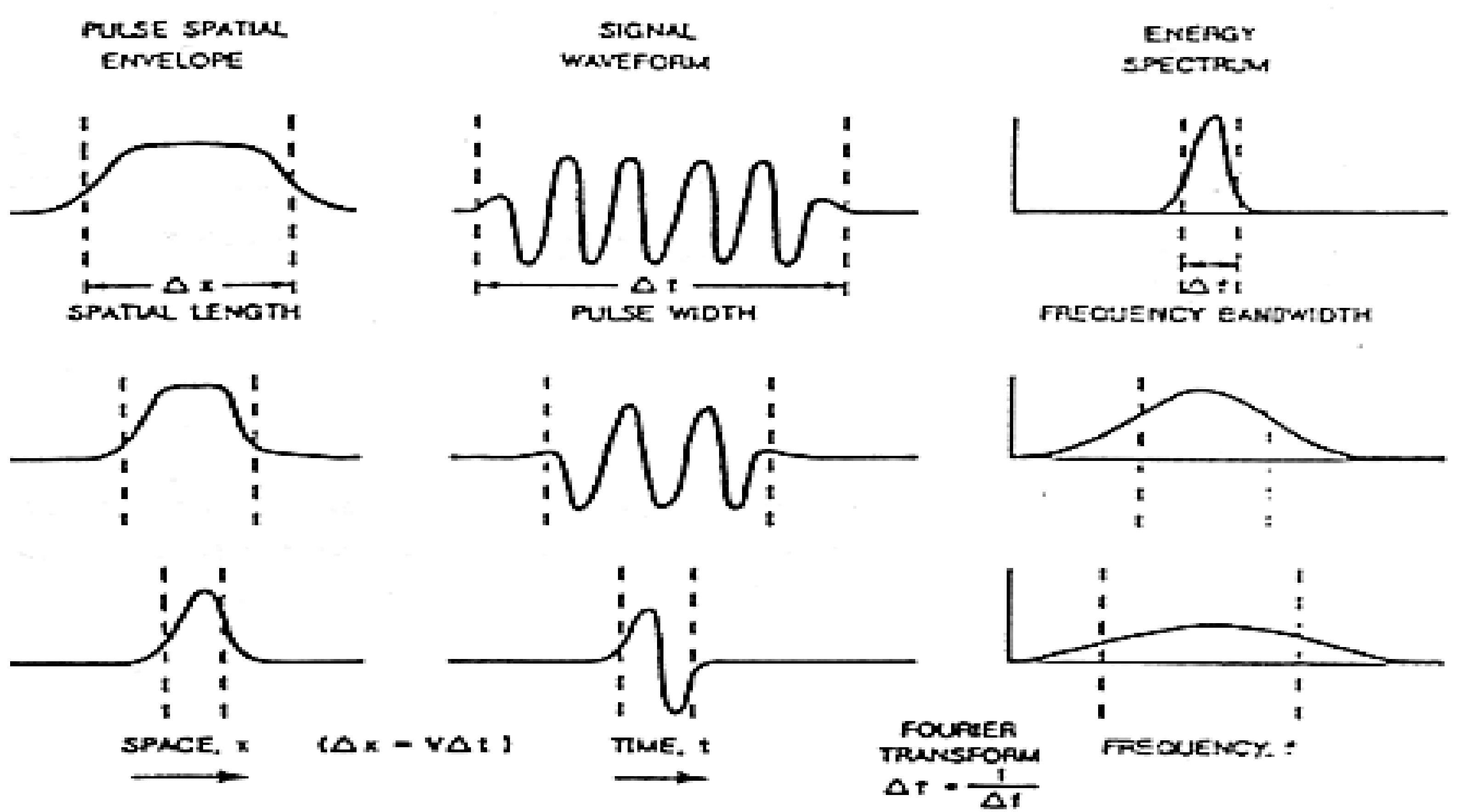
GPR Signal

- Modulated sinusoids with a center frequency to produce a "seismic-type" source wavelet.

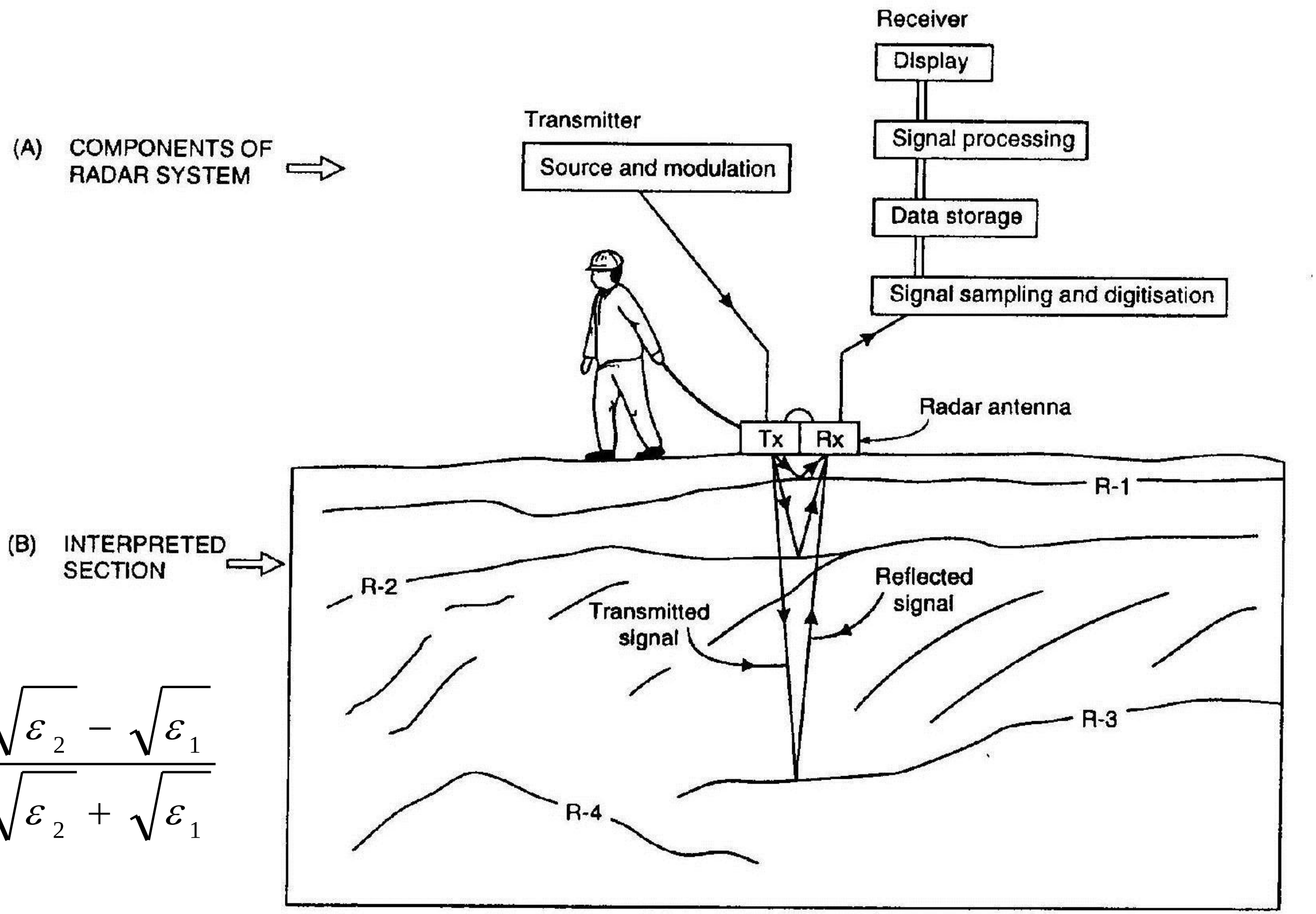


- Needs many frequencies to produce a narrow signal. Bandwidth is usually about equal to the center frequency

GPR signals and bandwidth



GPR Ground Penetrating Radar



$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}}$$

GPR Signals: Wave Propagation

- Packets of energy
- Travel with constant velocity in a uniform medium
- Reflect at boundaries
- Refract according to Snell's law
- Fundamental of refraction seismology apply to GPR

Electromagnetics

- **FD Maxwell's equations ($e^{-i\omega t}$)**

$$\nabla \times \mathbf{E} - i\omega\mu\mathbf{H} = 0$$

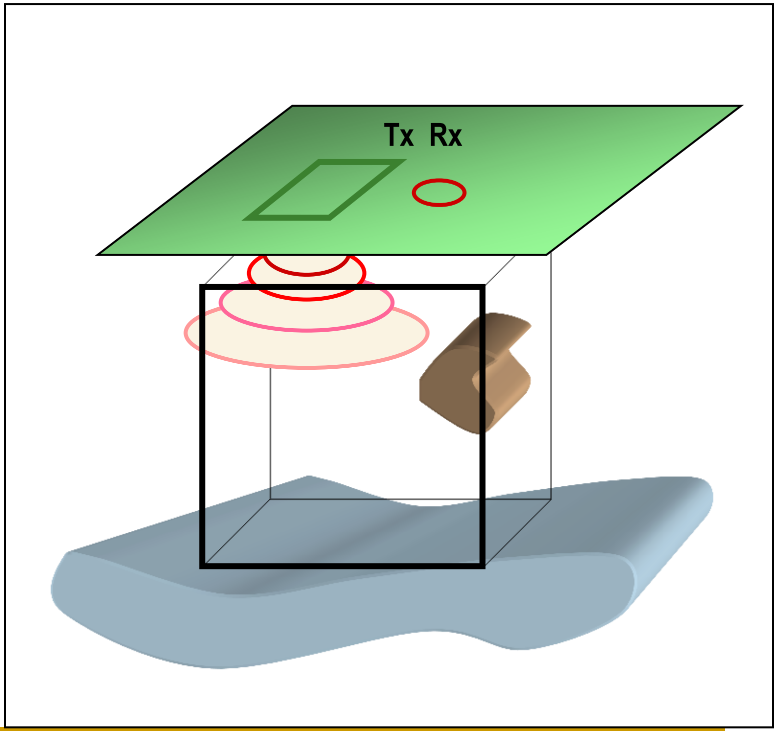
$$\nabla \times \mathbf{H} - (\sigma - i\omega\varepsilon)\mathbf{E} = \mathbf{J}^{e}$$

$$\nabla \cdot \varepsilon\mathbf{E} = 0$$

$$\nabla \cdot \mu\mathbf{H} = 0$$

E: electric field
H: magnetic field
J: current source density

Electromagnetic induction



Velocity – relationship to properties

Two assumptions are necessary

$\omega = 2\pi F$

- 1) **<u>If</u>** $\sigma \ll \omega\varepsilon$ (low loss condition) **<u>then</u>**

$$V \approx \frac{1}{\sqrt{\mu\varepsilon}}, \quad where \quad \mu = \mu_0 \mu_R \quad and \quad \varepsilon' = \varepsilon_0 \varepsilon_R$$

$$\approx \frac{1}{\sqrt{\mu_0 \mu_R \varepsilon_0 \varepsilon_R}}$$

$$V \approx \frac{C}{\sqrt{\mu_R \varepsilon_R}} \quad because \quad \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = C$$

ε_R and μ_R are ratios hence unitless

  - ε_0 and μ_0 are dielectric permittivity and magnetic permeability of free space. C is speed of light in vacuum.

Dielectric permittivity

- Water has strongest effect on ε in geologic materials.
- **Velocity** of radar signals is (usually) most affected by ε.

Table of relative dielectric permittivity (e_R), electrical conductivity (σ), and velocity.

Material	e_R		V avg (m/ns)
Air	1		.3
Distilled water	80		0.033
Fresh water	80		0.033
Sea water	80		0.01
Dry sand	3- 5		0.15
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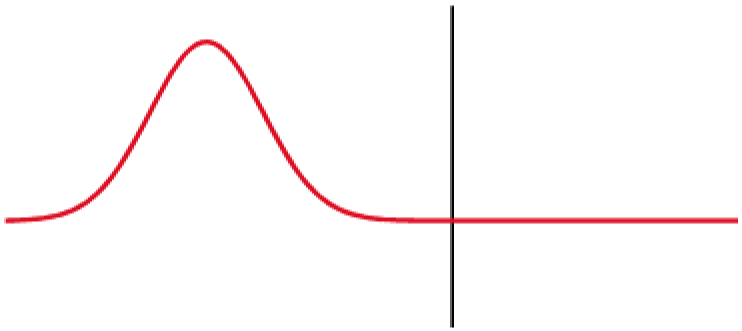
Clays	5-40		0.06
Granite	4-6		0.13
Dry salt	5-6		0.13
Ice	3-4		0.16

Transmission/reflection coefficient

- The equation for the reflection coefficient R is:

$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}}$$



- For water, ε_2 = 80, take ε_1=1
- Solve for R = 0.8
- Amplitude of transmitted wave = 1-R = 0.2

- At a water/free space interface, the amplitude of the transmitted wave is only **20%** of the incident wave.

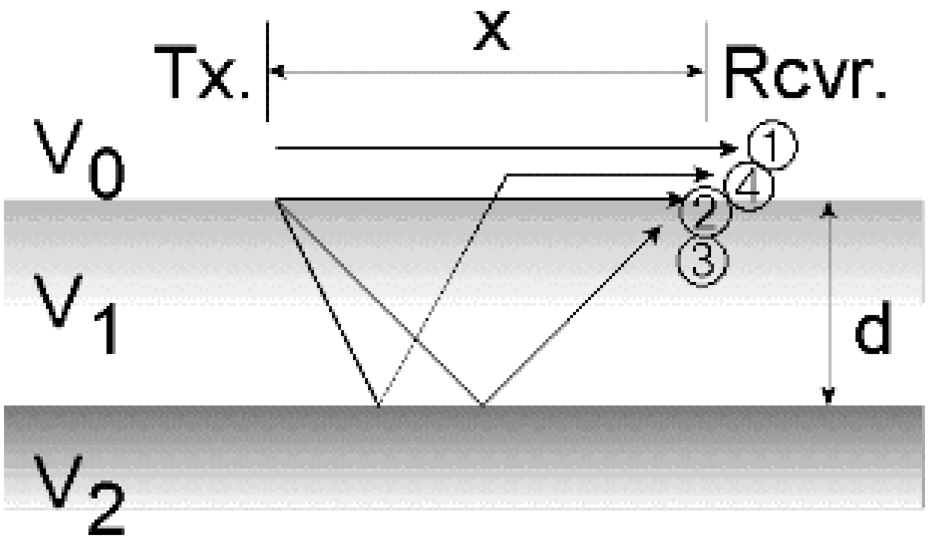
Snell's Law for GPR

- Snell's law also applies to GPR:

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

- Yields refracted waves
- Can obtain critically refracted waves (head waves) This is the same as in seismic refraction.

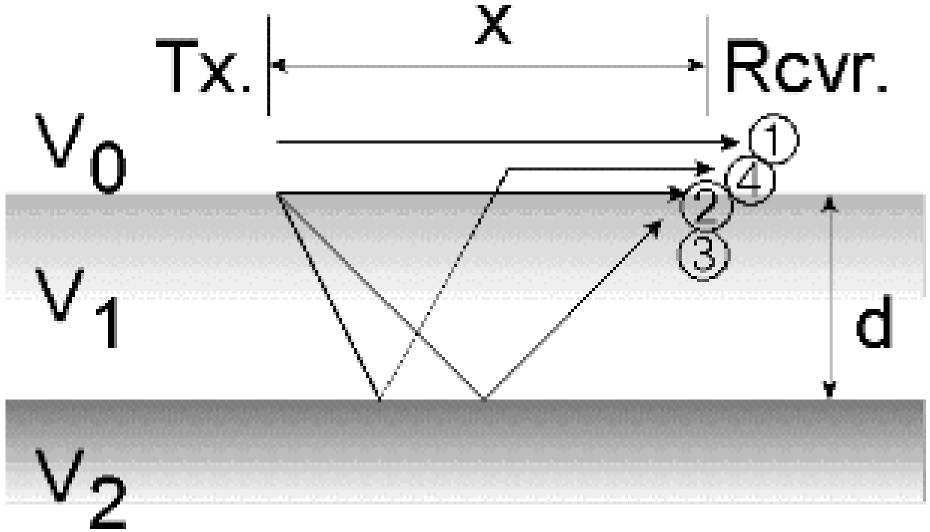
GPR waves



- Direct air wave (1)
- Direct ground wave (2)
- Reflected wave (3)
- Critically refracted wave(4)

Note: Velocity of air is higher so there is a critically refracted wave going from earth to air

Interpreting GPR wave



Eq'ns for signal travel times

① Direct air wave: $t(x) = x/V_0$.

② Direct ground wave: $t(x) = x/V_1$.

③ Reflected wave: $t(x) = \dfrac{\sqrt{x^2 + 4d^2}}{V_1}$.

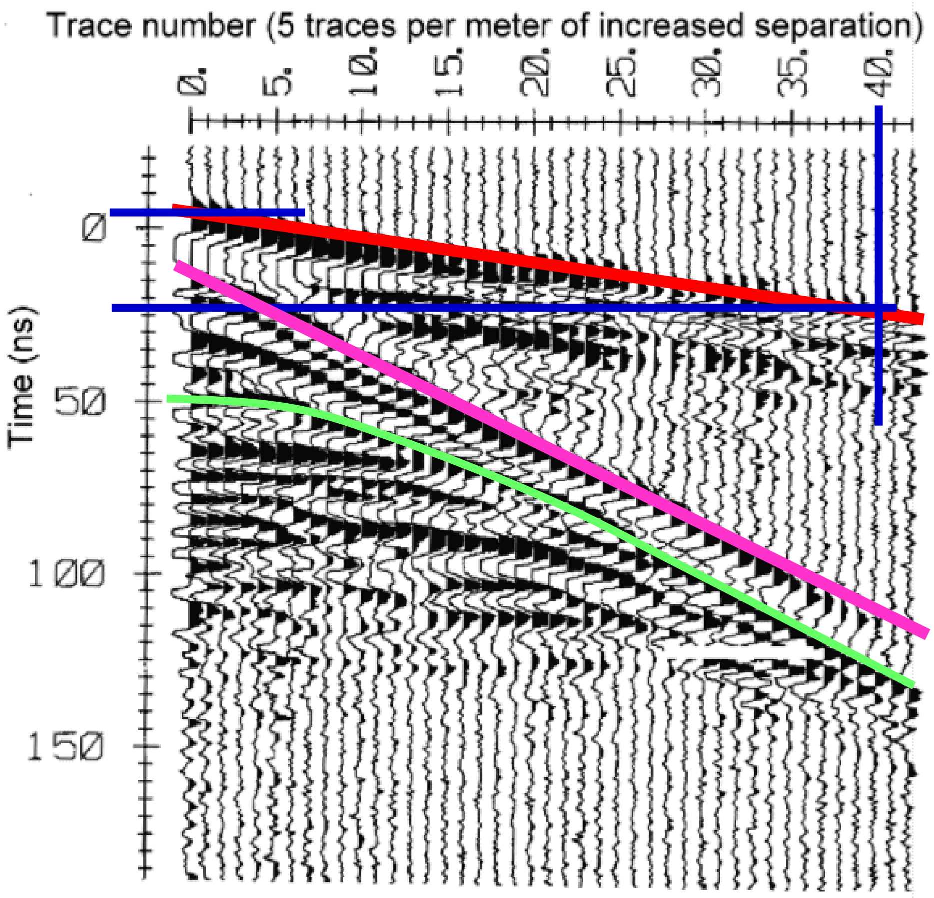
④ Critically refracted wave:

$t(x) = x/V_0 + const$

Velocities

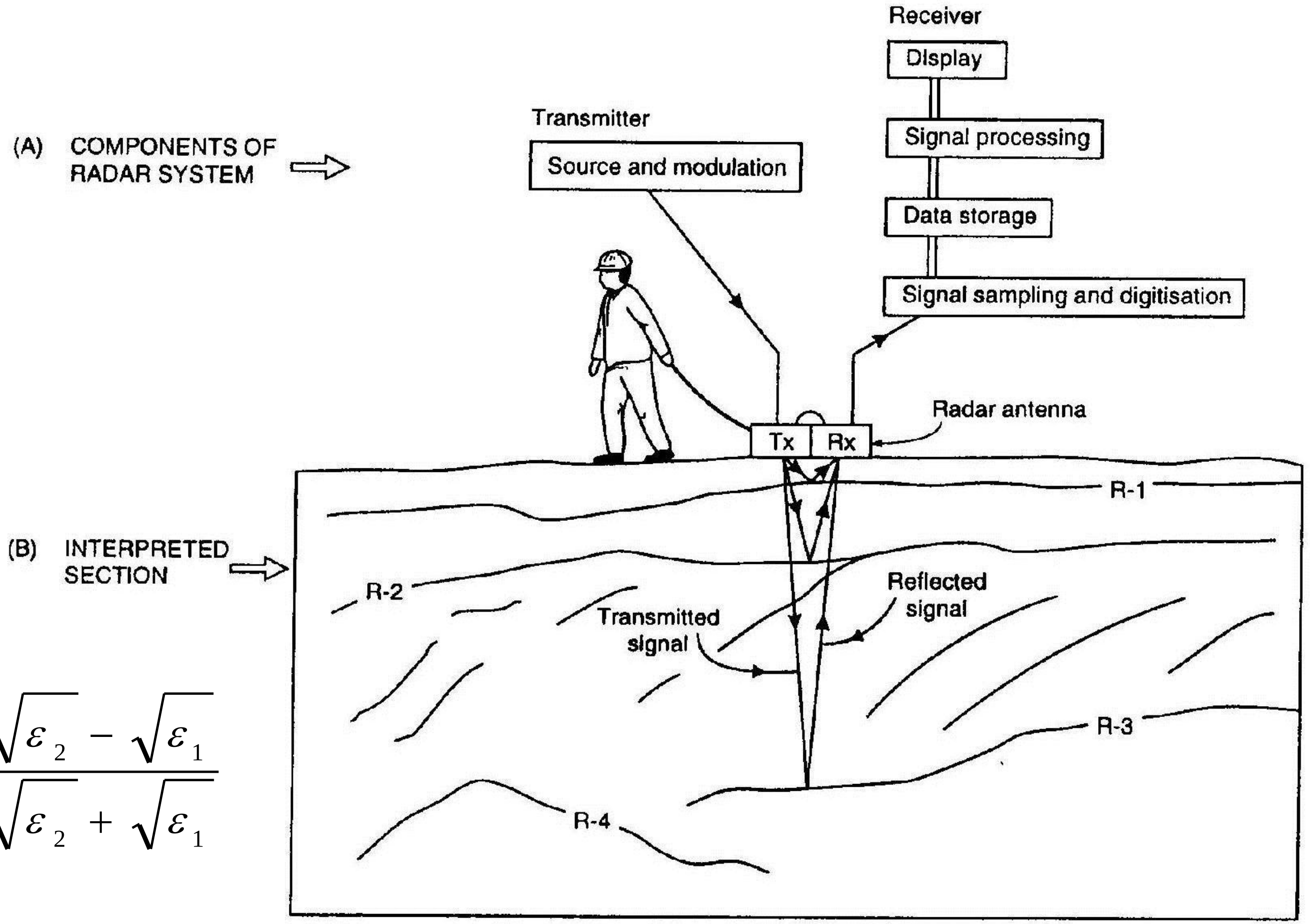
- Related to properties via

$$V \approx \frac{C}{\sqrt{\varepsilon}}; \qquad C = 3 \times 10^{8} \; m/s$$



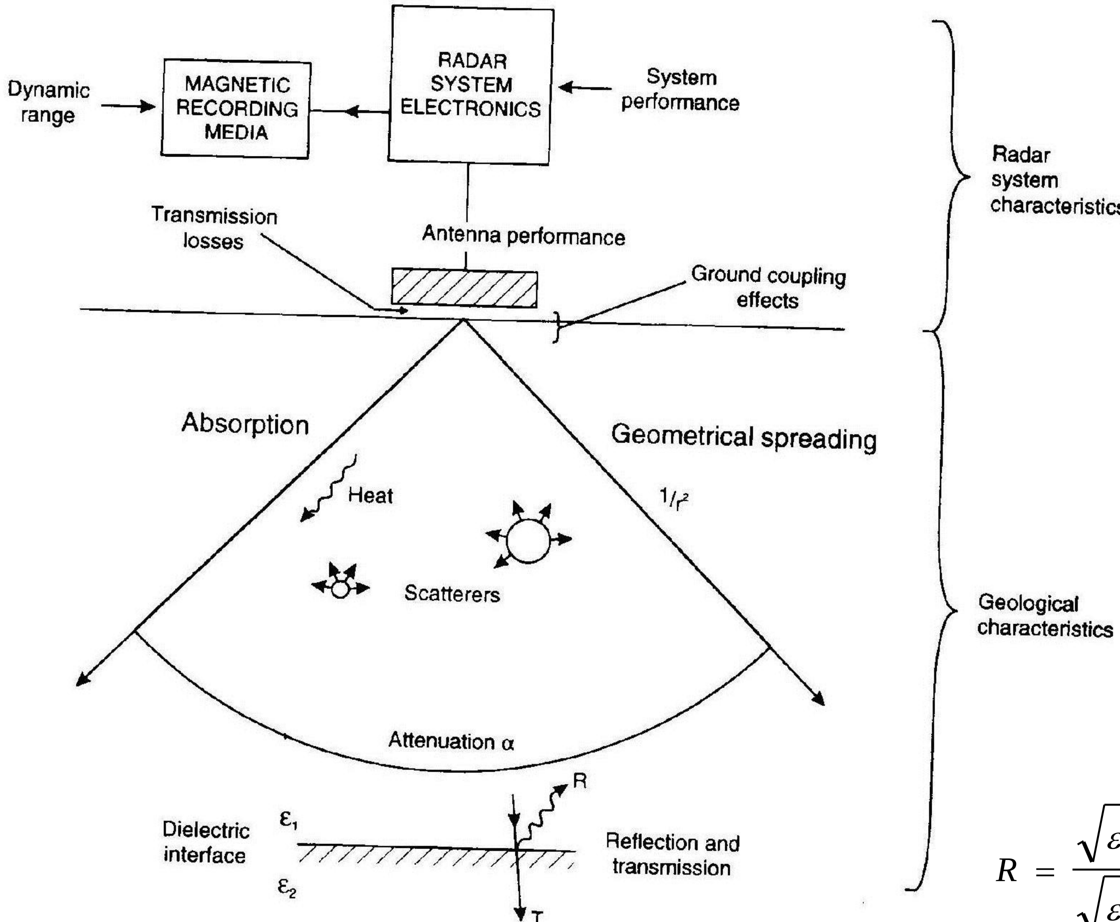
- Example record.
  - GPR data with different Tx-Rx distances.
  - Straight lines give air & top layer velocities
  - Hyperbolas yield average velocity of top layer (see GPG notes)

GPR Ground Penetrating Radar



$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}}$$

Attenuation of GPR signals



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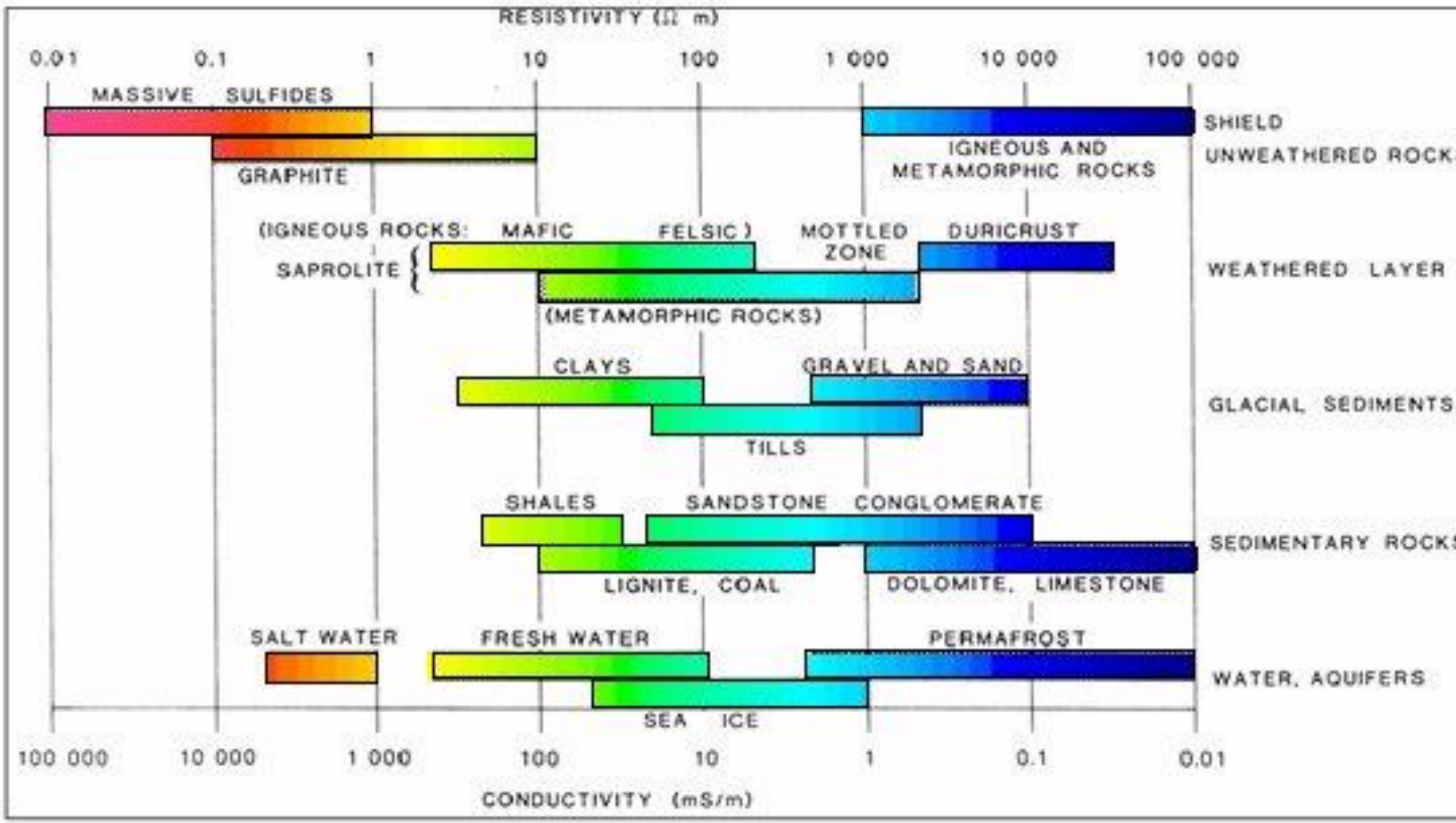
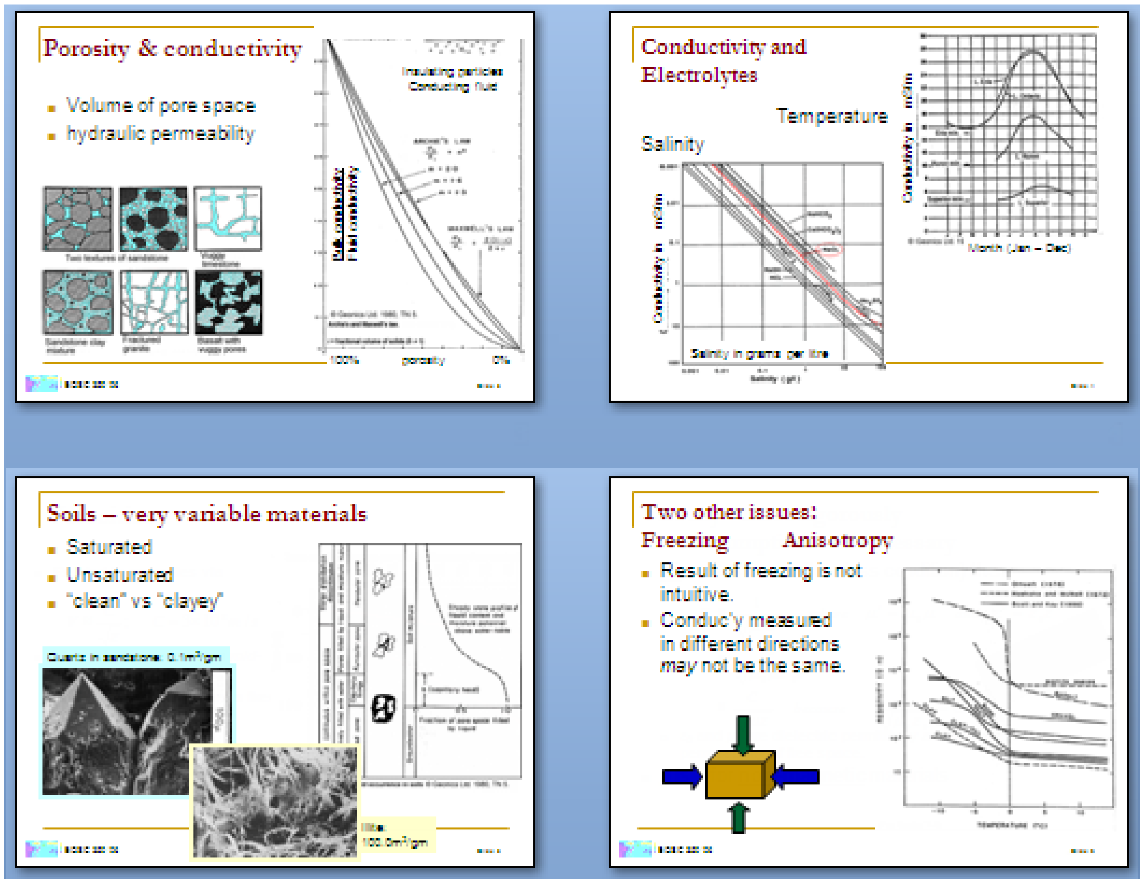
Consider conductivity – GPR point of view

- 7 orders of magnitude
- Matrix materials mainly insulators
- Therefore fluids and porosity are key



From Second week of term

Many reasons why geology ←→ conductivity is complicated …



Attenuation of GPR signals

- The strength of the EM radiation gets weaker the further away from the source

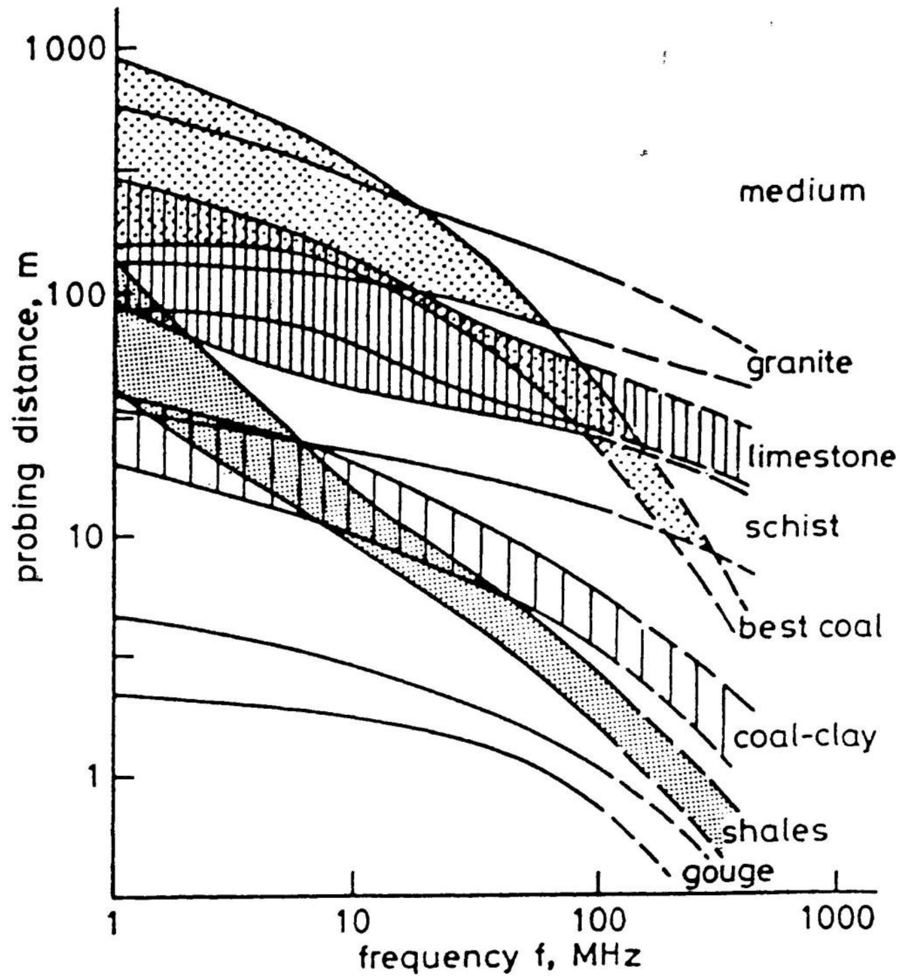
- The concept of “skin depth” is the distance at which the signal has decreased to 1/e (that is ~37%)

$$\delta = \left(5.31\sqrt{\varepsilon_r}\right)/\,\sigma \quad \text{meters}$$

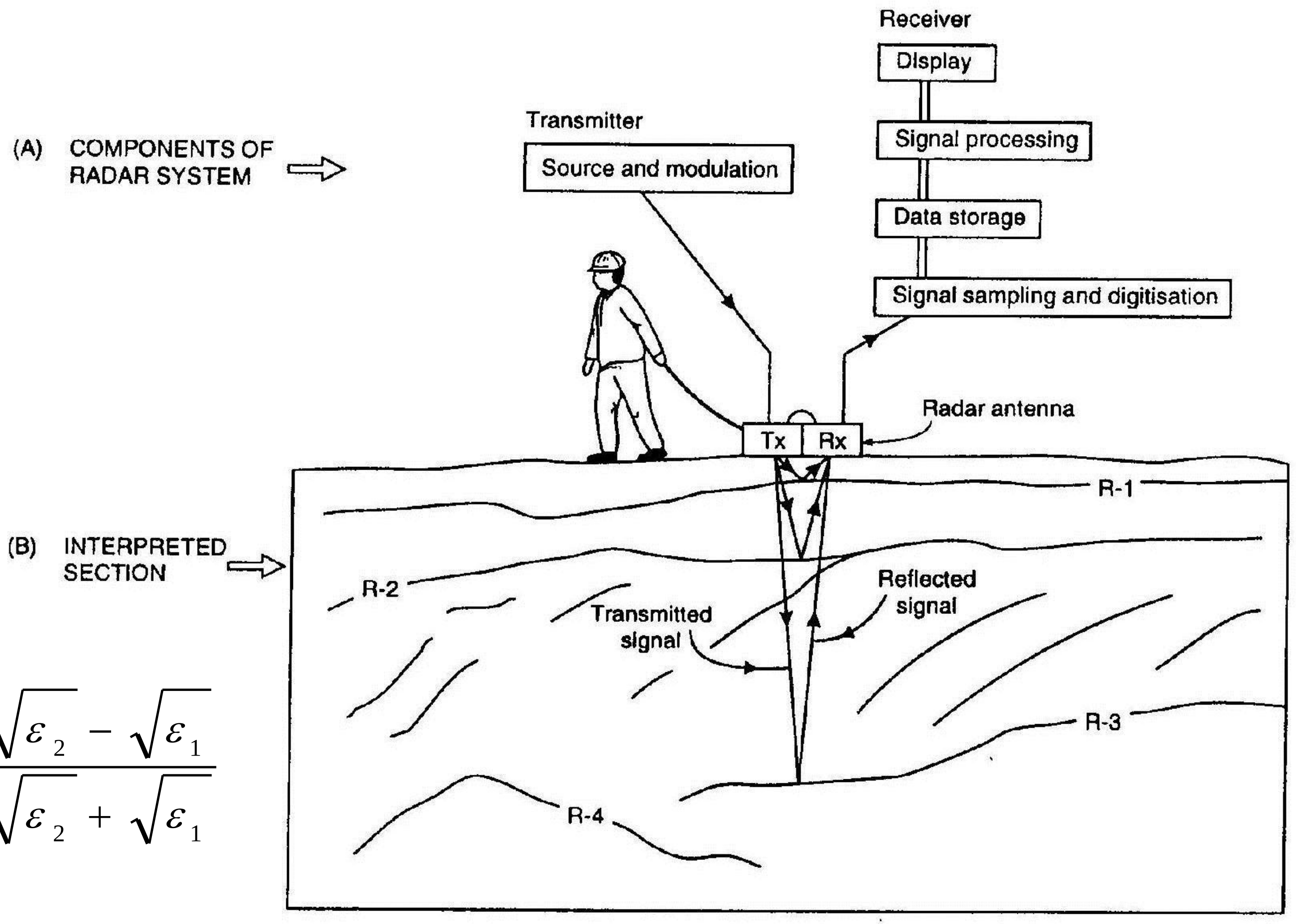
Conductivity in mS/m (milli-Semens per meter)

GPR probing distance

Keep in mind that GPR probing distance is highly dependent on the amount of moisture/water content of the material



Summary: GPR Ground Penetrating Radar



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Di-electric constant, conductivity, velocity

- Water has is extremely important
- **Attenuation** of radar signals is most affected by σ..

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Attenuation of GPR signals

- Wave velocity

$$V \approx \frac{C}{\sqrt{\varepsilon}}; \qquad C = 3 \times 10^{8} \, m/s$$

- Reflection coefficient

$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}}$$

- Refraction

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

- Skin Depth (meters)
  Conductivity in mS/m
  (milli-Siemens per meter)

$$\delta = \left(5.31 \sqrt{\varepsilon_r}\right) / \sigma$$

GPR Readings

- GPG section 3.g