Magneto-telluric and Very Low Frequency EM methods

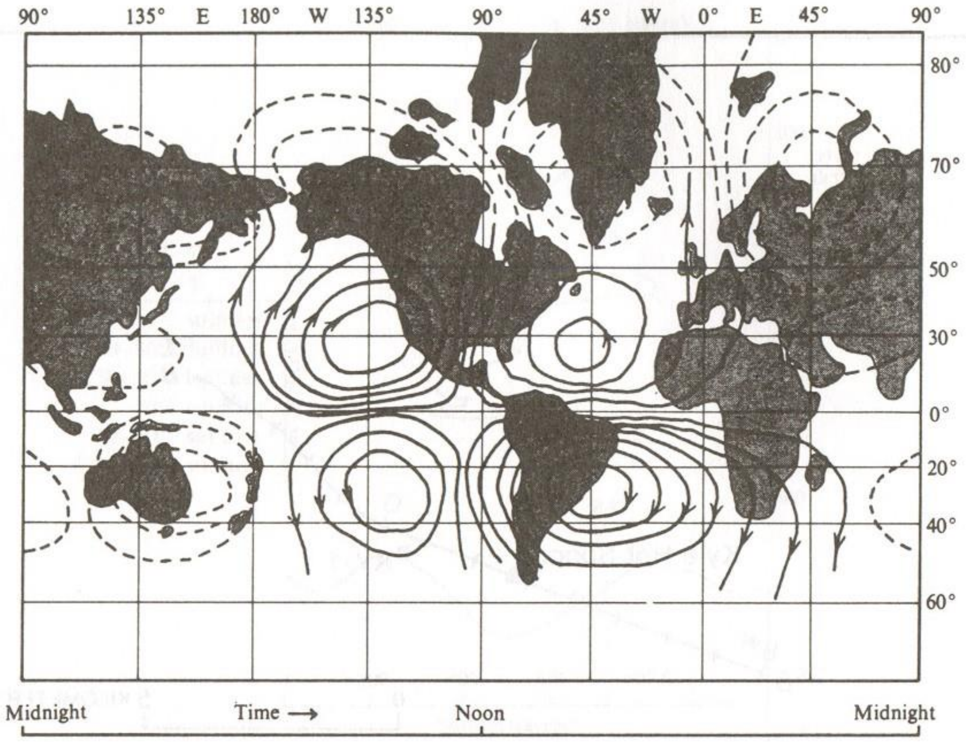
In this lecture, we discuss two EM techniques using almost plane waves (recall the end of the preceding lecture) from natural and artificial sources

- Magneto-telluric (MT) method
    - Telluric currents
    - Instrumentation
- Very Low Frequency (VLF) method
    - VLF sources
- Interpretation
    - Apparent resistivity
    - VLF tilt angle

- Reading:
    - Reynolds, Chapter 12
    - Dentith and Mudge, online appendix 4 at www.cambrige.org/dentith (MT only)
    - Telford et al., Chapter 6

Magneto-telluric (MT) method

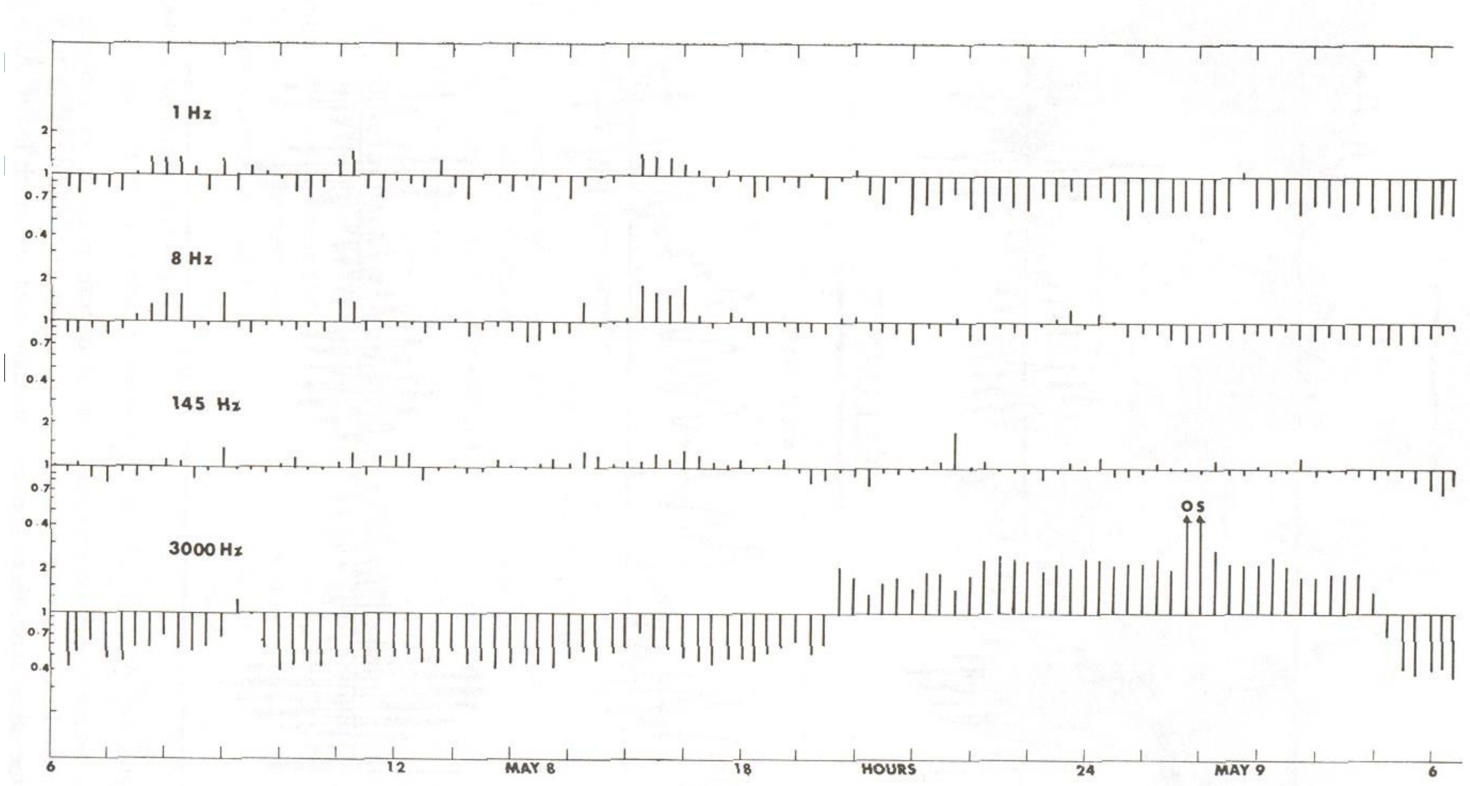
- Uses naturally occurring electromagnetic waves generated by electrical currents within the ionosphere, electric storms, lightning
- Relatively low-frequency EM waves bouncing back and forth between the Earth's surface and ionosphere
  - Frequencies 10^{-5} to 10^{5} Hz (10^{-3} to 10^{3} Hz used in MT work)
  - Mostly vertically-propagating EM waves. i.e. both **E** and **H** are near-horizontal



Patterns of telluric currents

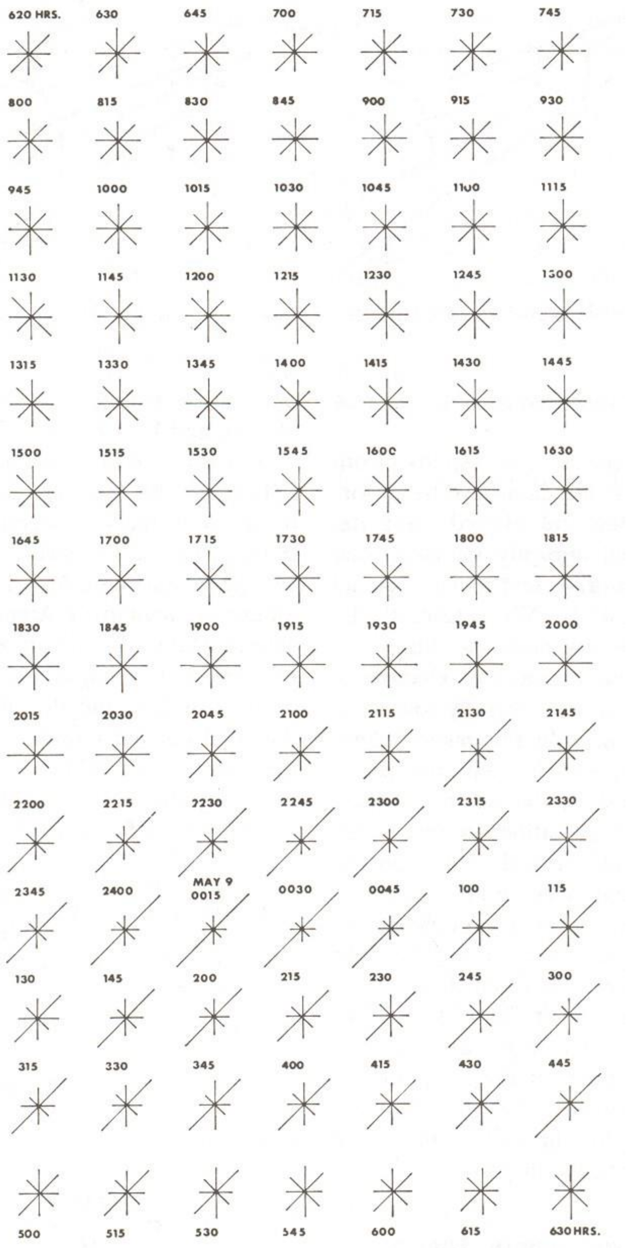
Telluric currents - amplitudes

- Plot below shows MT amplitudes at 15-min intervals at several frequencies, relative to their average levels
- Note that higher-frequency MT signal is below 50% from about 10 am to 8 pm
  - This may be good for lower-frequency MT work



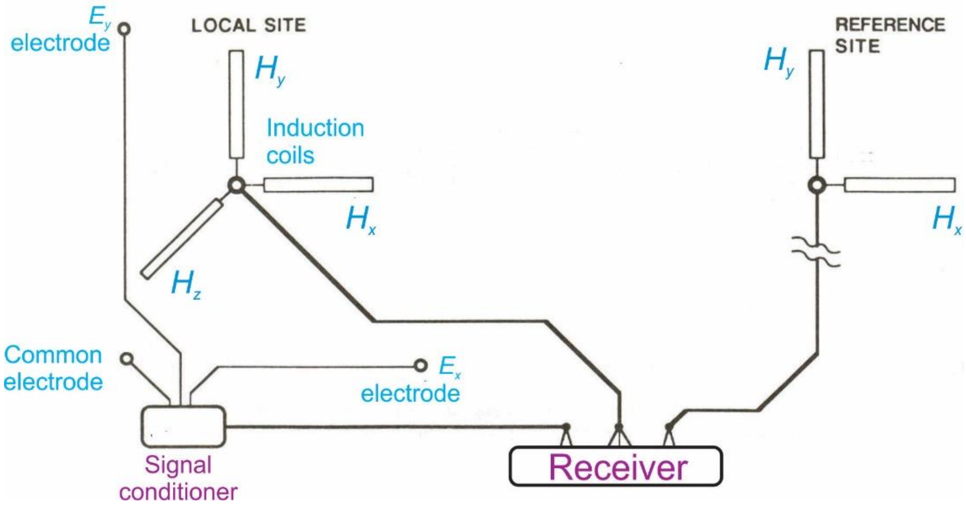
Telluric currents – azimuthal variations

- Azimuthal variations of amplitudes are also lower at around 2 pm
- Thus, 6 to 8 hours around 2 pm is a convenient window for MT measurements



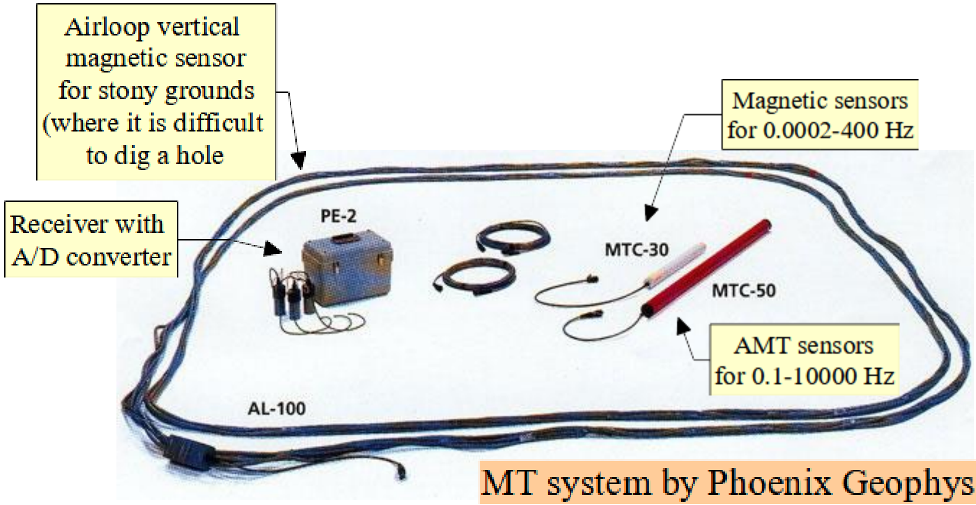
Magneto-telluric measurements

- Reference (similar to "base" in gravity) site is usually needed to measure time variations (drift) of telluric currents
- Magnetic coils are usually buried to avoid shaking
- Audio-frequency range MT (AMT) can also use a controlled source in the form of a grounded electric dipole



Setting up an H_x coil in 2019 Geophysics Field School (Phoenix Geophysical)

Non-polarizable electrode



Airloop vertical magnetic sensor for stony grounds (where it is difficult to dig a hole

Receiver with A/D converter

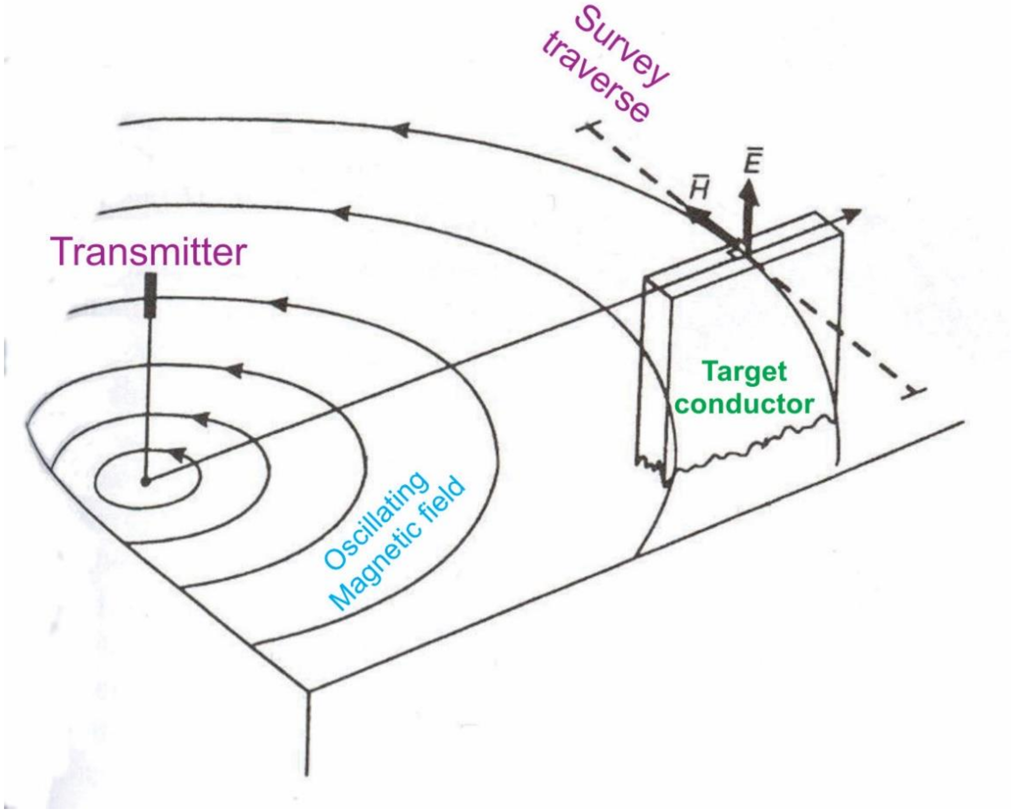
Magnetic sensors for 0.0002-400 Hz

AMT sensors for 0.1-10000 Hz

MT system by Phoenix Geophysics

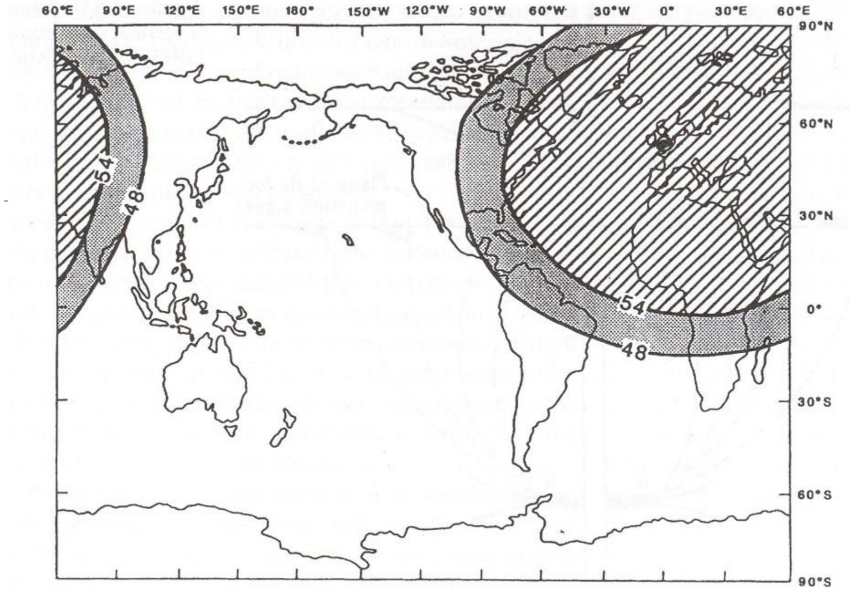
VLF method

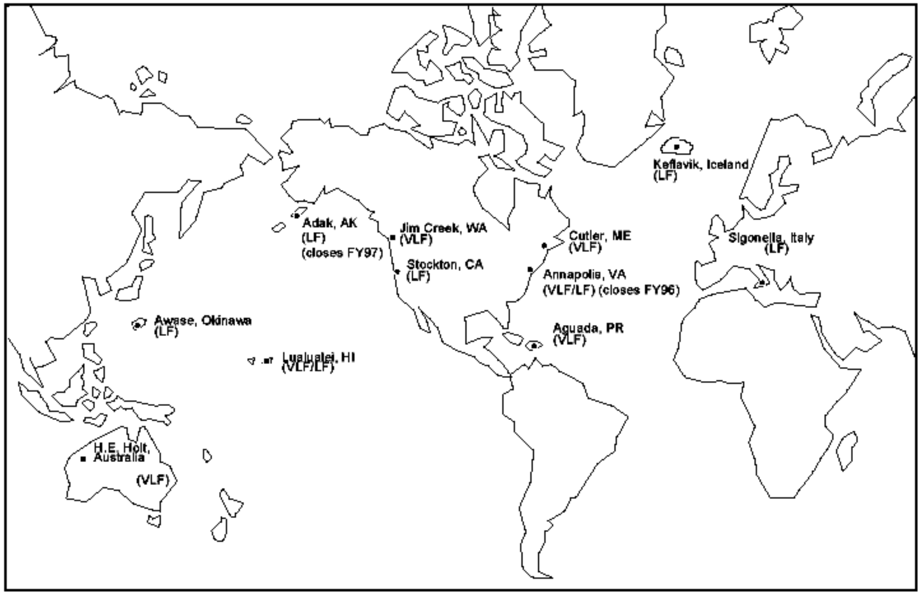
- Powerful radio transmitter (Tx) with vertical antenna creates horizontally-polarized magnetic field at low frequency (figure below). This is the primary VLF field.
  - As in most EM methods, the wave propagates away from the source, but the wavelength is long (~15 km), and the field can be viewed as spatially uniform
- The field is polarized with **E** (electric) field oriented vertically, and **H** horizontally sideways from the direction to the transmitter
  - Therefore, VLF surveying is done in a direction perpendicular to the direction to the Tx (figure)
- Thus, a conductor oriented along the direction toward the Tx supports currents induced both by **E** and the oscillating **H**
  - These currents create secondary magnetic and electric fields that are measured by the VLF receiver



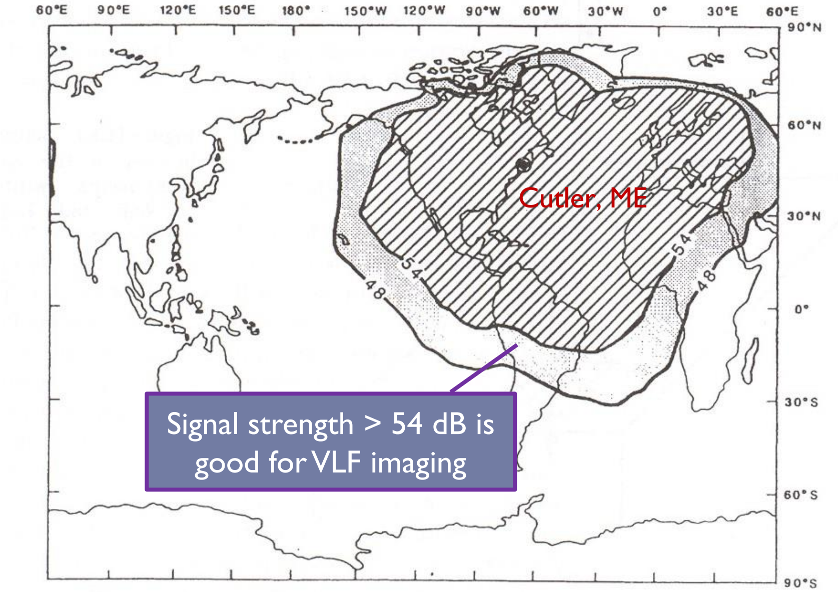
VLF transmitters

- There are currently about 11 powerful (> 1 MWt) VLF transmitters around the world, operating at 15-24 kHz
  - Theis primary designation is of course not for geophysics but for marine navigation and communication with submarines





Very Low Frequency/Low Frequency Site Locations



Signal strength > 54 dB is good for VLF imaging

MT and VLF interpretation

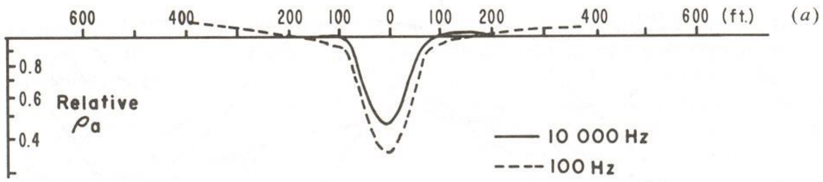
- Interpretation of MT and VLF is often based on the relation for apparent resistivity from horizontal components of **E** and **H** fields
- Recall from the preceding lecture that, for example, **E** and **H** fields on the surface of a conductor are orthogonal, and their amplitudes are mutually related due to the skin-layer effect
  - This relation is caused by the resistivity of the medium
  - From the ratio of **E** and **H** amplitudes, the apparent resistivity is:

$$\rho_a = \frac{1}{\omega\mu_0}\frac{\left\langle E_x^2\right\rangle}{\left\langle H_y^2\right\rangle} = \frac{1}{\omega\mu_0}\frac{\left\langle E_y^2\right\rangle}{\left\langle H_x^2\right\rangle} \approx 0.2T\frac{\left\langle E_H^2\right\rangle}{\left\langle H_H^2\right\rangle}$$

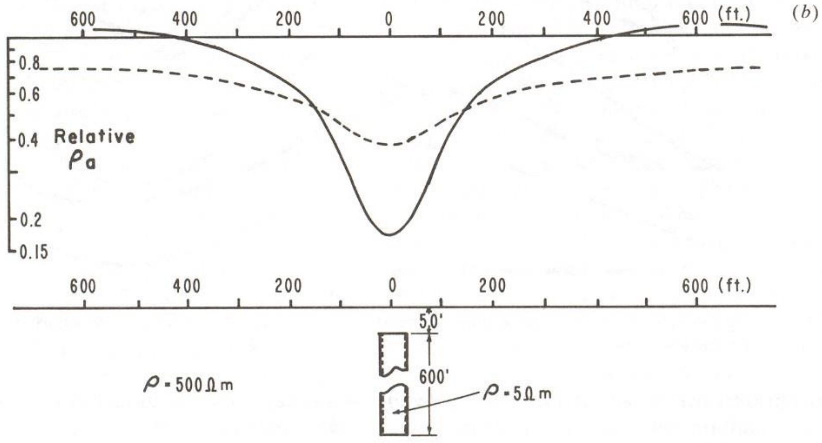
Here,
E in [mV/km]
H in [nT]
T in [sec] – wave period

- When evaluated for different orientations, this ρ_a can actually be different (plot on the right)

With **E** perpendicular to conductor



With **E** parallel to conductor

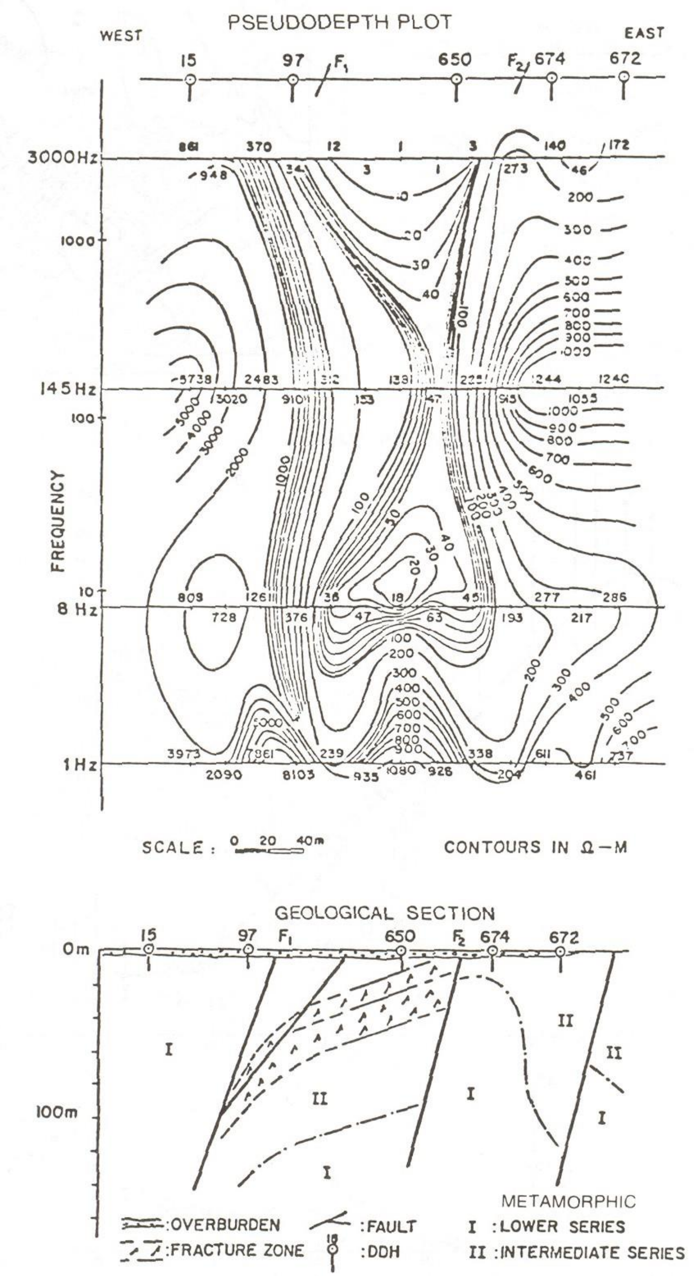


MT example

- To display apparent-resistivity MT section, the frequency is plotted in descending order and logarithmic scale downward and often viewed as "pseudo-depth"
- The pseudo-depth is the skin depth at some reference resistivity ρ_0:

$$\text{pseudo-depth} = \delta(f) = \sqrt{\frac{\rho_0}{\pi\mu_0}}\, f^{-1/2}$$

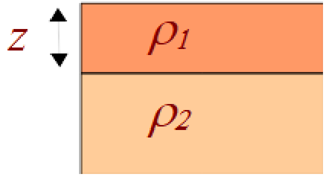
- Figures on the right show such a pseudo-depth ρ_a section and a geological section of Coxwell dome in northern Saskatchewan



From Telford et al. text

MT and VLF depth sounding

- The apparent resistivity ρ_a in MT and VLF depends on frequency. This dependence allows constraining true conductivity variations with depth



- For example, for a single layer over a half space (Cagniard, 1953), the apparent resistivity scaled by resistivity of the layer is a function of scaled frequency $\gamma = 2z\sqrt{\frac{\omega\mu}{2\rho_1}} = \frac{2z}{z_s} \approx 0.004z\sqrt{\frac{f}{\rho_1}}$:

$$\frac{\rho_a}{\rho_1}(\gamma) = \frac{\alpha^2 e^{2\gamma} + 2\alpha e^{\gamma}\cos\gamma + 1}{\alpha^2 e^{2\gamma} - 2\alpha e^{\gamma}\cos\gamma + 1}$$

, where

$$\alpha = \frac{\sqrt{\rho_2/\rho_1} + 1}{\sqrt{\rho_2/\rho_1} - 1}$$

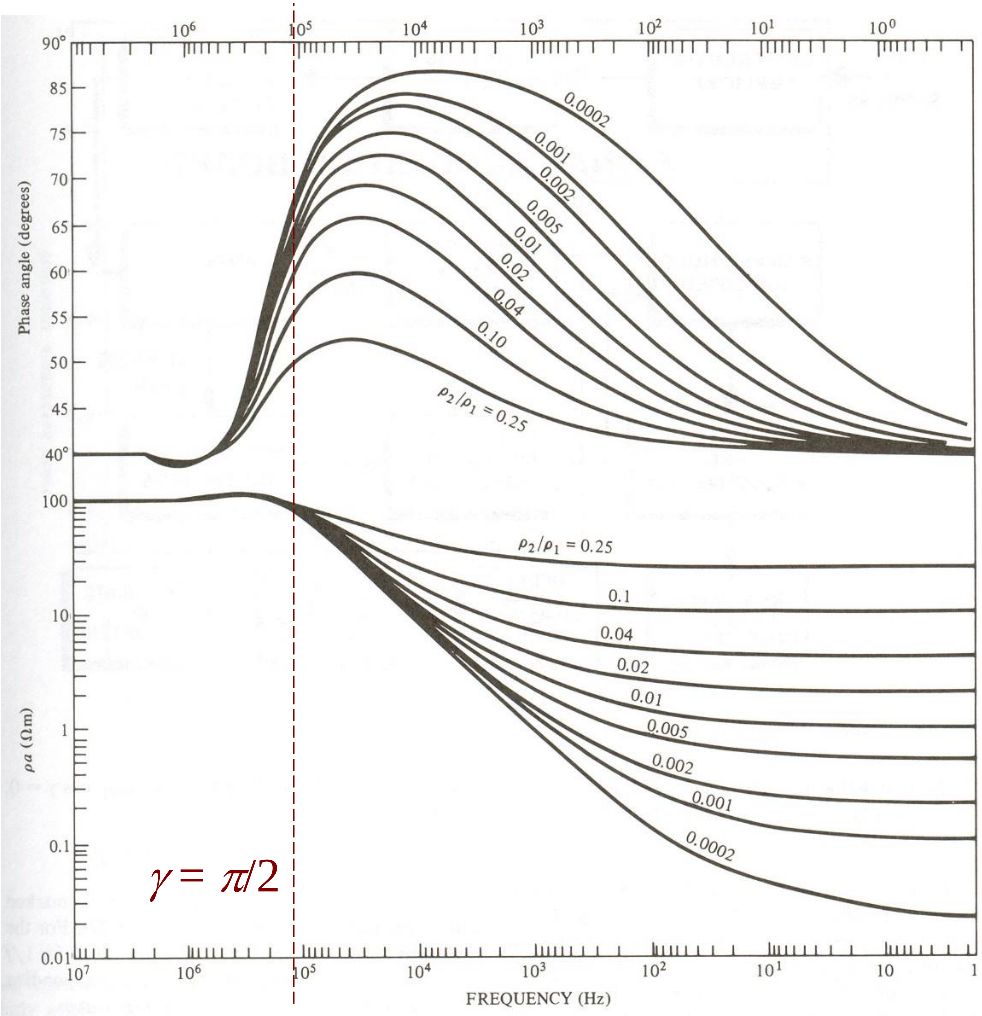
- Thus (similar to resistivity in a two-layer medium), we can invert $\rho_a(f)$ data for as two-layer model like this:

1. Precompute master curves of $\rho_a(\gamma)/\rho_1$
2. Plot the measured f and ρ_a on log-log scales
3. By shifting the measured curves and matching the master curves, find ρ_1 and ρ_2/ρ_1
4. Find in the graphs f_s for which $\gamma = \pi/2$ (this basically means that z is the skin depth at frequency f_s; see next slides). From this f_s, depth of the resistivity contrast z is estimated:

$$z \approx 250\gamma\sqrt{\frac{2\rho_1}{f_s}} \approx 400\sqrt{\frac{2\rho_1}{f_s}}$$

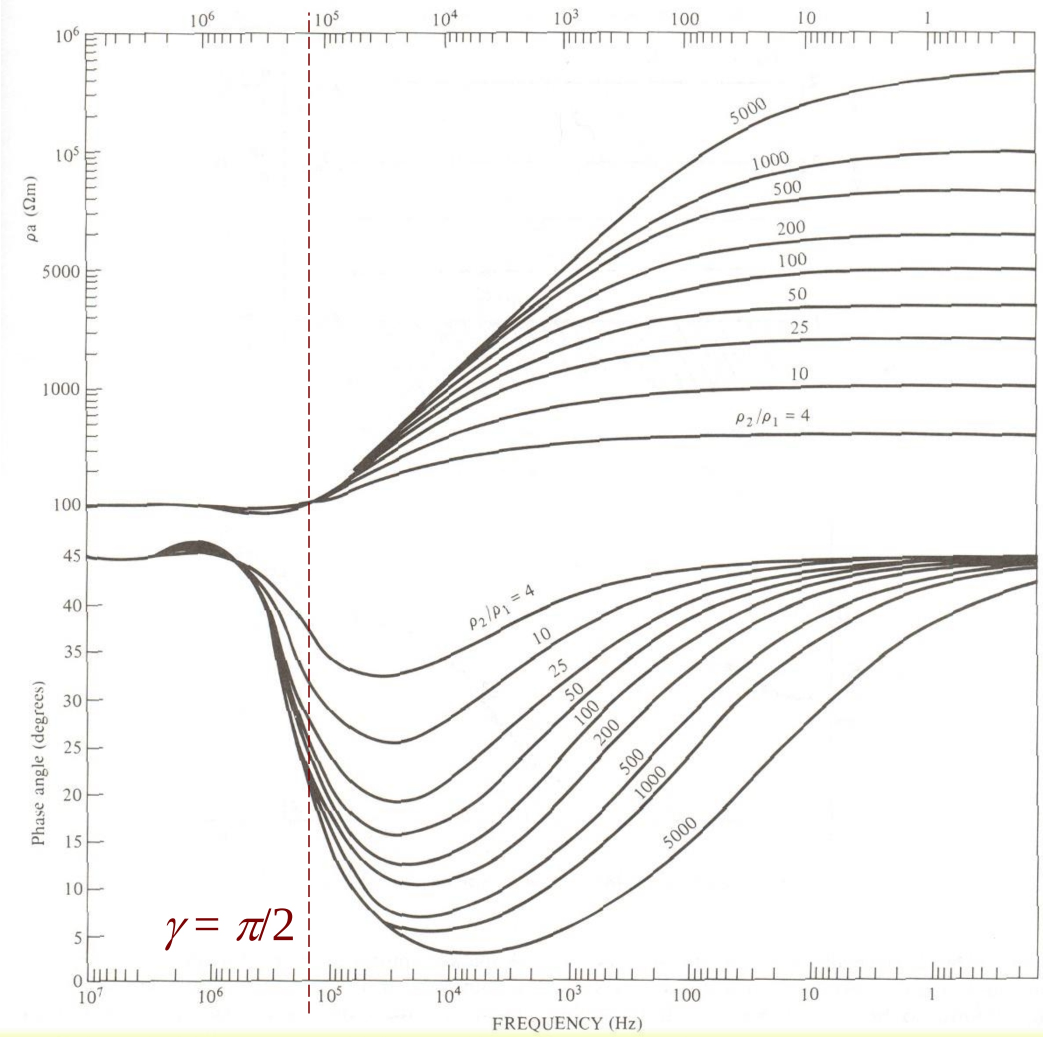
Extra note for GEOL334

AMT master curves ($\rho_2 < \rho_1$)



Extra note for GEOL334

AMT master curves ($\rho_2 > \rho_1$)



VLF tilt angle

- Due to dense profiling, "tilt angle" interpretation is also convenient for VLF
  - Tilt angle (θ in the figure) is a convenient indicator for locating conductive anomalies when using a uniform primary field (such as in VLF)
- Tilt angle can be obtained by taking ratio of H_z to H_x amplitudes or by tilting Rx coil to obtain a minimum signal
- θ changes from downward to upward over an anomaly
  - $\theta = 0$ indicates the conductive anomaly