Lecture 17

Magnetotellurics

GEOL 4397: Electromagnetic Methods for Exploration
GEOL 6398: Special Problems

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Nov. 15th, 2018

UNIVERSITY of HOUSTON
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EARTH AND ATMOSPHERIC SCIENCES

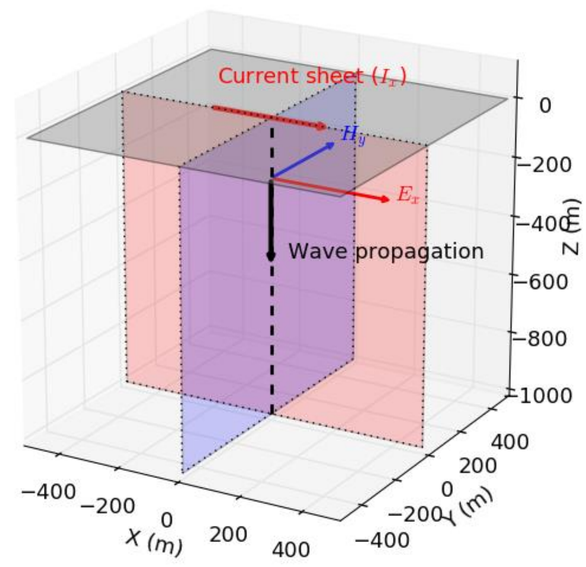
Agenda

- Recap
  - apparent resistivity
  - phase
- Numerical examples
- Case studies:
  - Geothermal exploration
  - Imaging of mantle upwelling

How to estimate the subsurface resistivity?

$$\rho(\omega) = \frac{1}{\sigma} = \frac{1}{\omega\mu}|Z(\omega)|^2$$

Where $$Z(\omega) = \frac{E_x(0,w)}{H_y(0,w)}$$



$Z(\omega)$ is termed impedance

From impedance, we can estimate the subsurface resistivity
For a homogeneous Earth, it gives the true resistivity
For a non-homogeneous Earth, it is apparent resistivity

Apparent resistivity

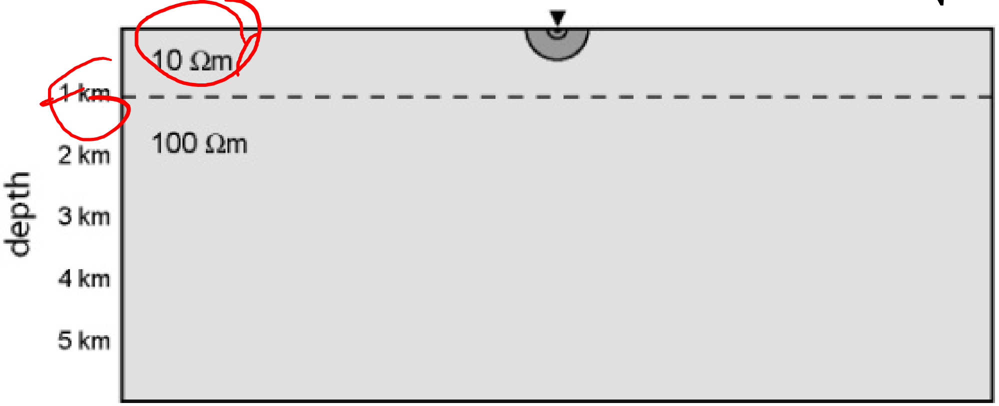
- Can be considered as average resistivity of the Earth down to skin depth

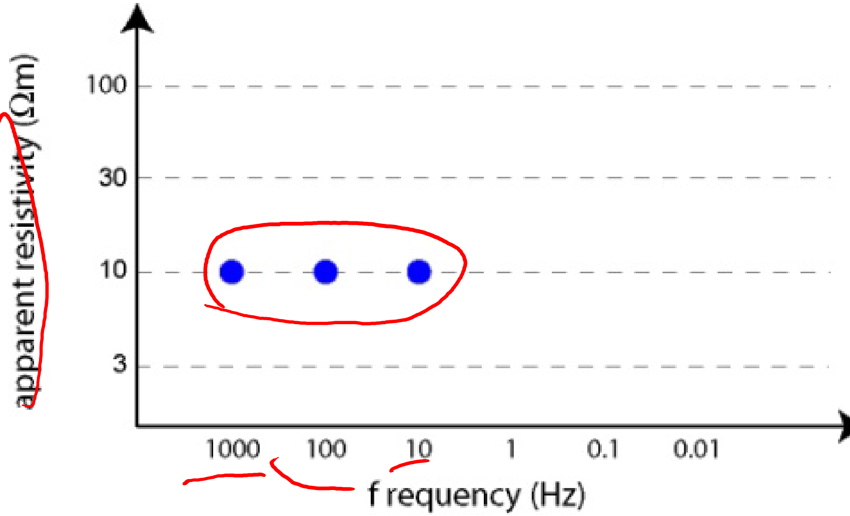
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = 503\sqrt{\frac{1}{\sigma f}}$$

- At higher frequency, it is the average resistivity of the shallower part of the Earth
- At lower frequency, it is the average resistivity of the Earth down to a greater depth.

Apparent resistivity: $f = 10$ Hz

$$\delta = 503\sqrt{\frac{1}{\sigma f}} = 500\ m$$



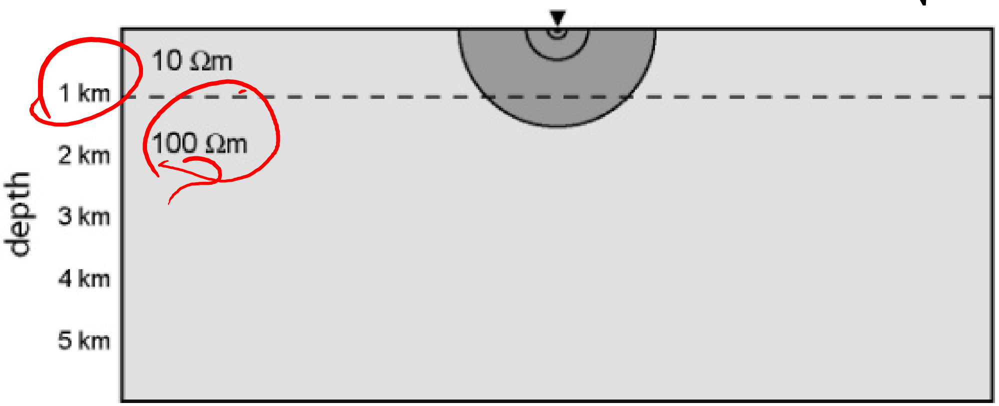


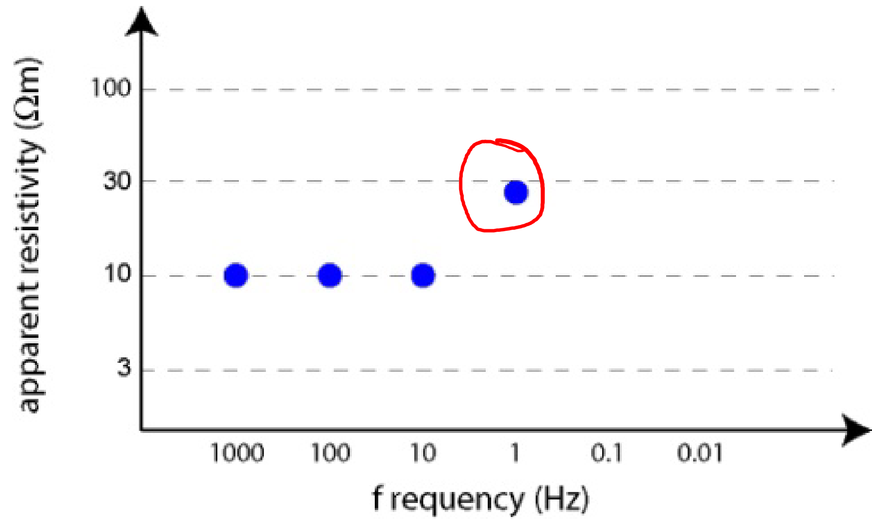
- At higher frequency, the skin depth is much smaller than the thickness of the layer
- Average resistivity is simply the resistivity of the upper layer

Credit: Martyn Unsworth, University of Alberta, 2013

Apparent resistivity: $f = 1$ Hz

$$\delta = 503\sqrt{\frac{1}{\sigma f}} = 1580\,m$$



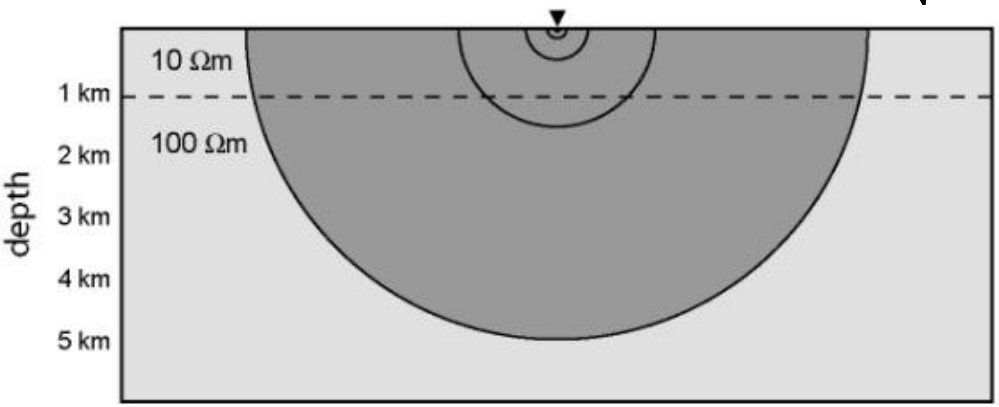


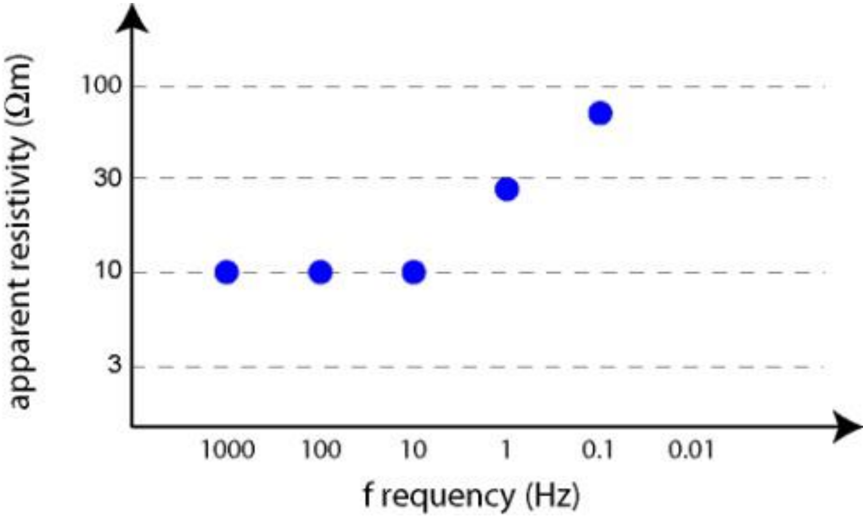
- The EM signals are now just sampling the lower layer.
- Average resistivity begins to increase as the lower resistive layer is being sampled.

Credit: Martyn Unsworth, University of Alberta, 2013

Apparent resistivity: $f = 0.1$ Hz

$$\delta = 503\sqrt{\frac{1}{\sigma f}} = 5000\,m$$



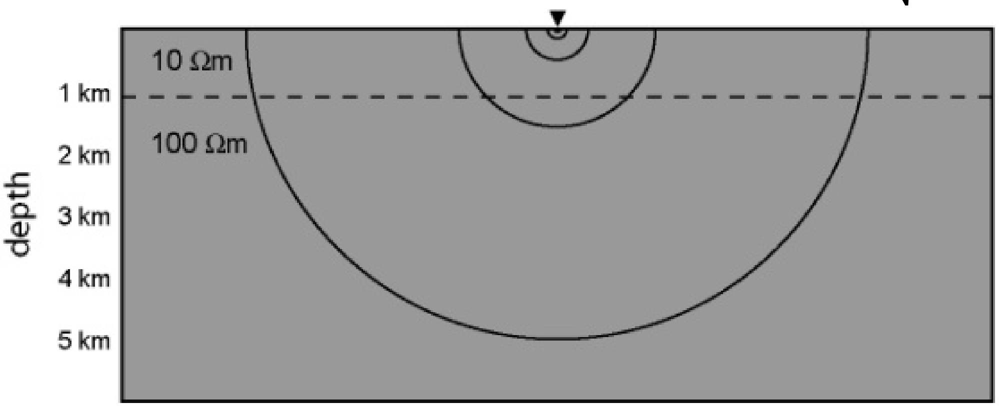


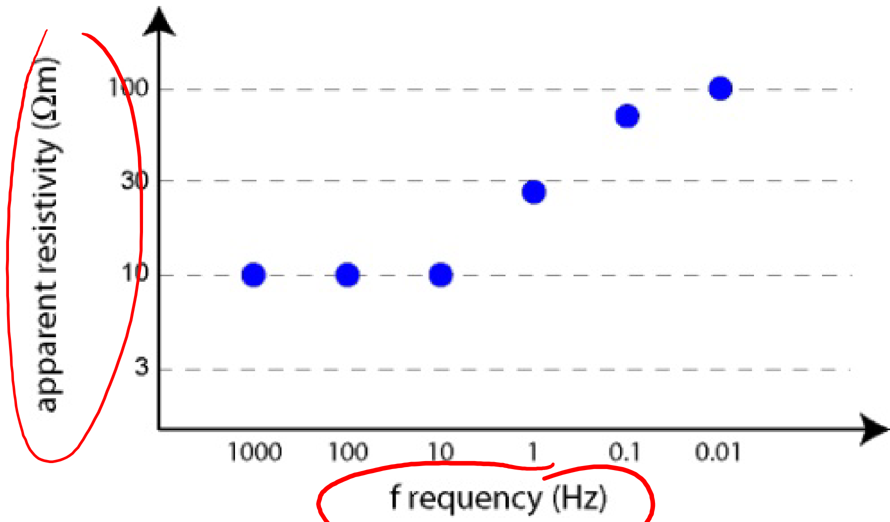
- The region that is sampled by EM signals is dominated by the lower layer
- Therefore, apparent resistivity is close to 100 Ωm.

Credit: Martyn Unsworth, University of Alberta, 2013

Apparent resistivity: f = 0.01 Hz

$$\delta = 503\sqrt{\frac{1}{\sigma f}} = 15800\ m$$





- Apparent resistivity approaches 100 Ωm asymptotically.

Credit: Martyn Unsworth, University of Alberta, 2013

Phase

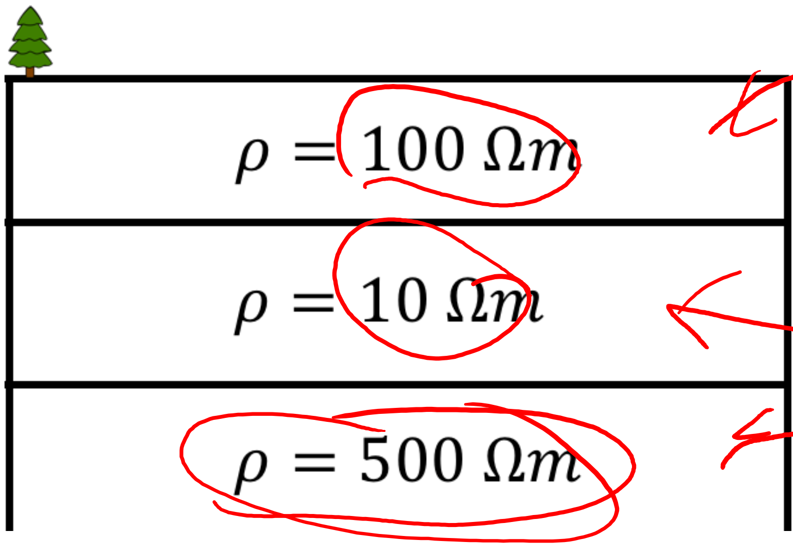
$$Z(\omega) = \frac{E_x(0,w)}{H_y(0,w)} = \sqrt{\frac{\omega\mu}{\sigma}}e^{i\frac{\pi}{4}}$$

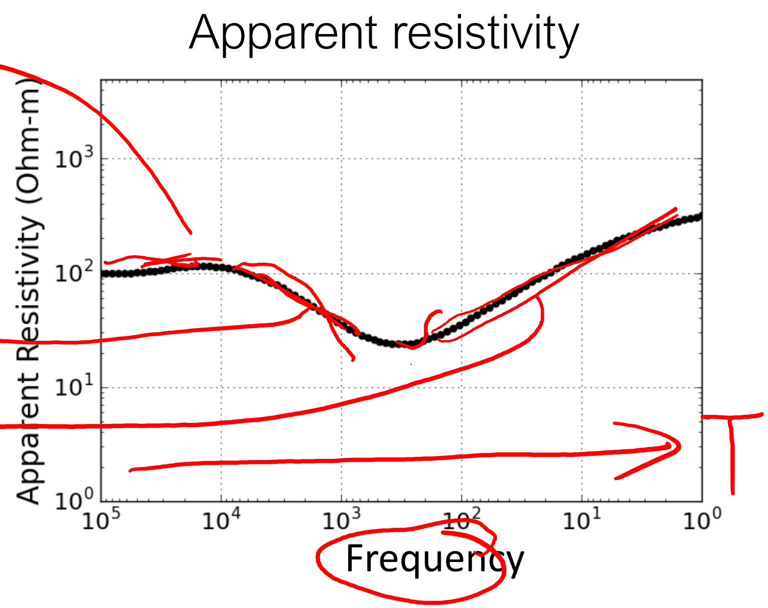
The phase $\phi(w) = \frac{\pi}{4}$

For homogeneous Earth, the phase is $\frac{\pi}{4}$

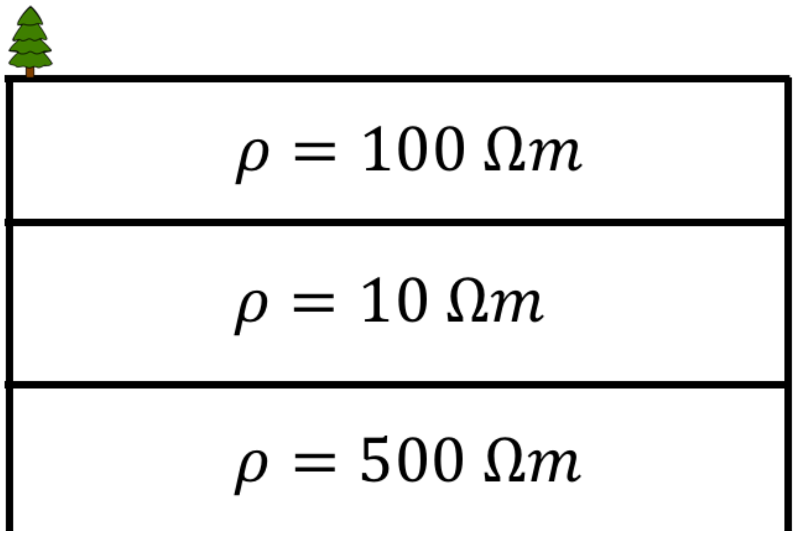
We can also plot the phase as a function of frequency (or period)

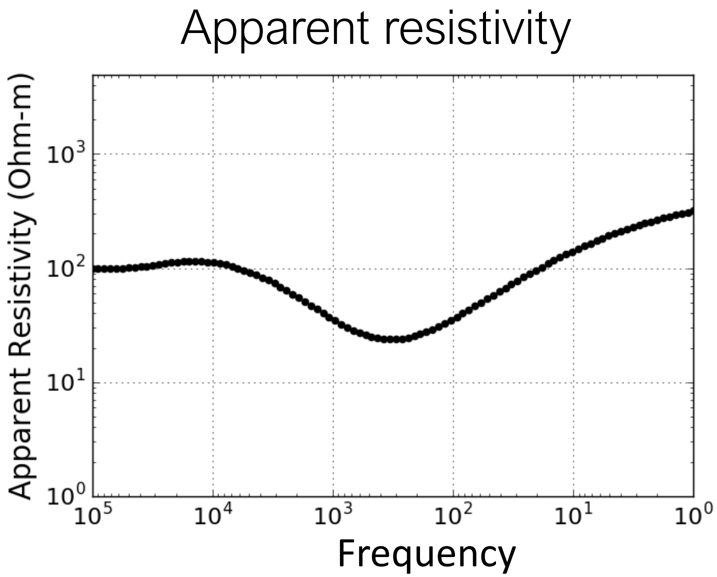
Three layer model





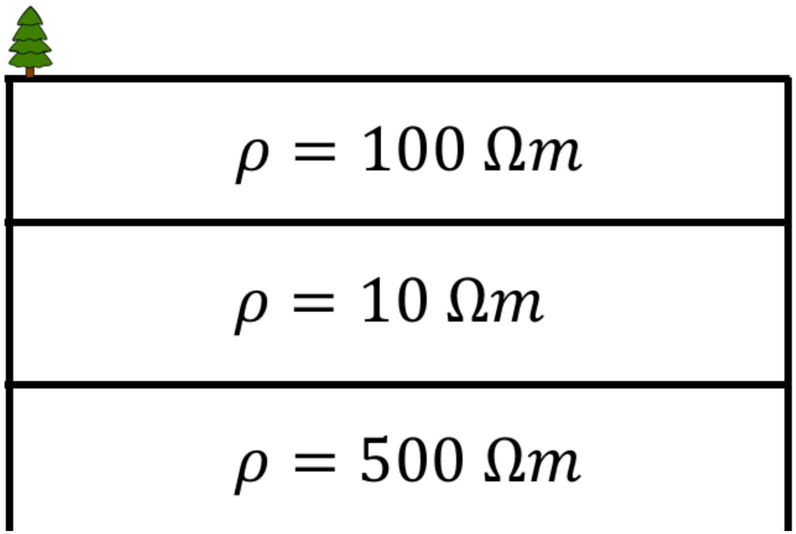
Three layer model

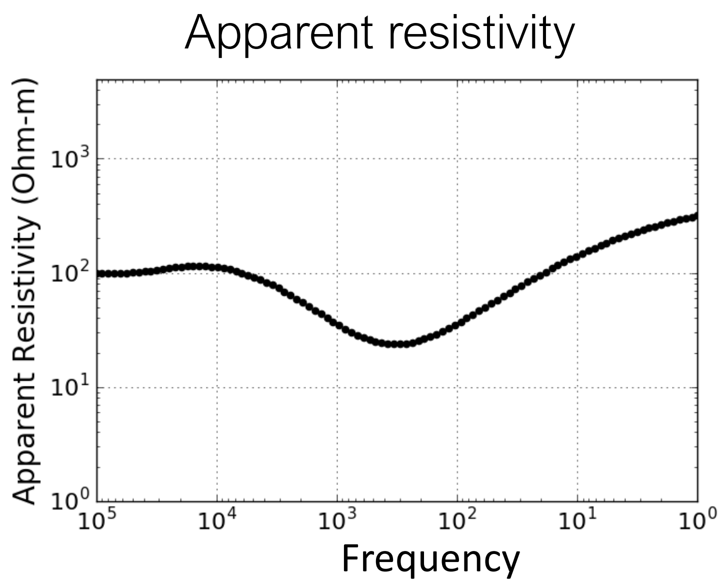




How about phase?

Three layer model: phase



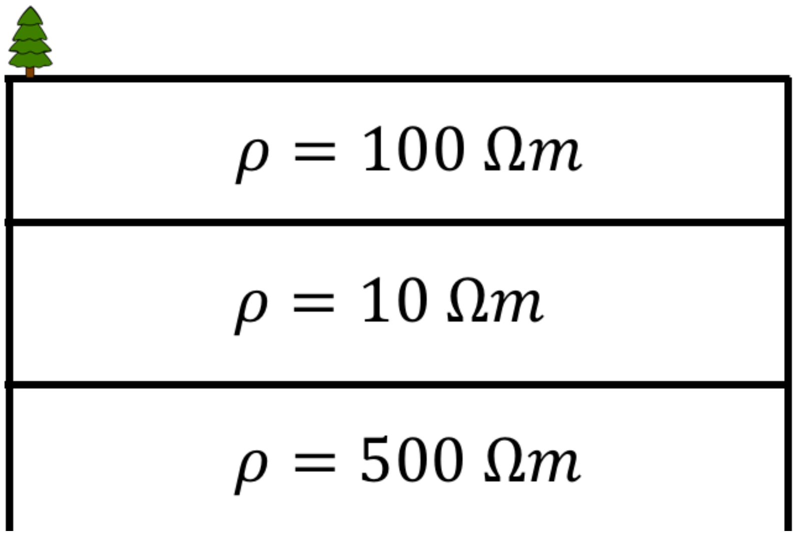


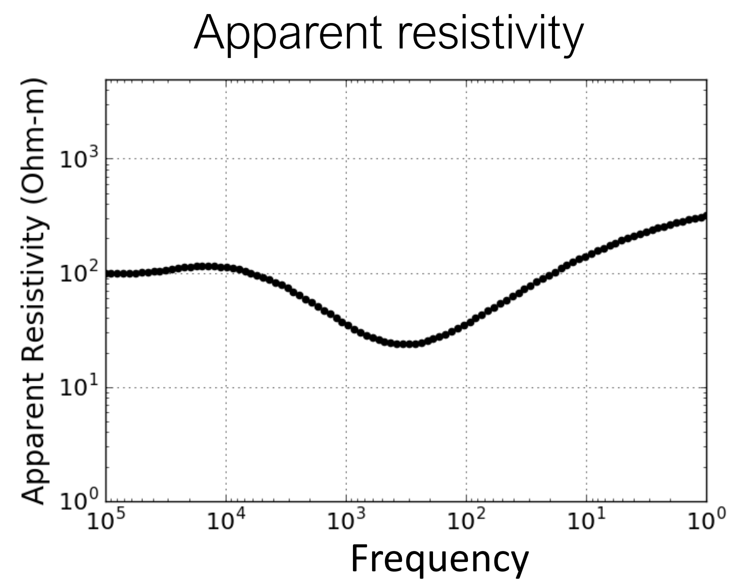
At very high frequency, the MT signals see a homogeneous Earth. Therefore, the phase is $\frac{\pi}{4}$.

At very low frequency, the lower halfspace dominates, and the MT signals see more or less a homogeneous Earth. Therefore, the phase is also $\frac{\pi}{4}$.

How about phase at intermediate frequencies?

Three layer model: phase





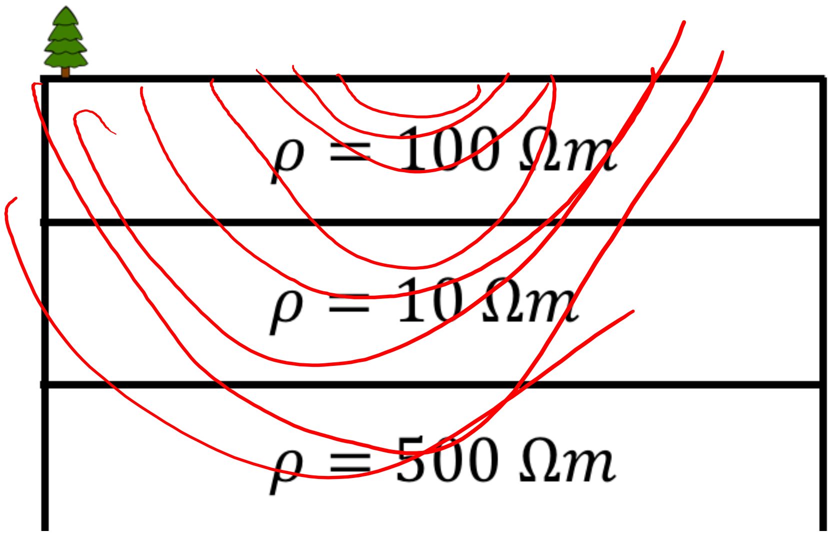
How about phase at intermediate frequencies?

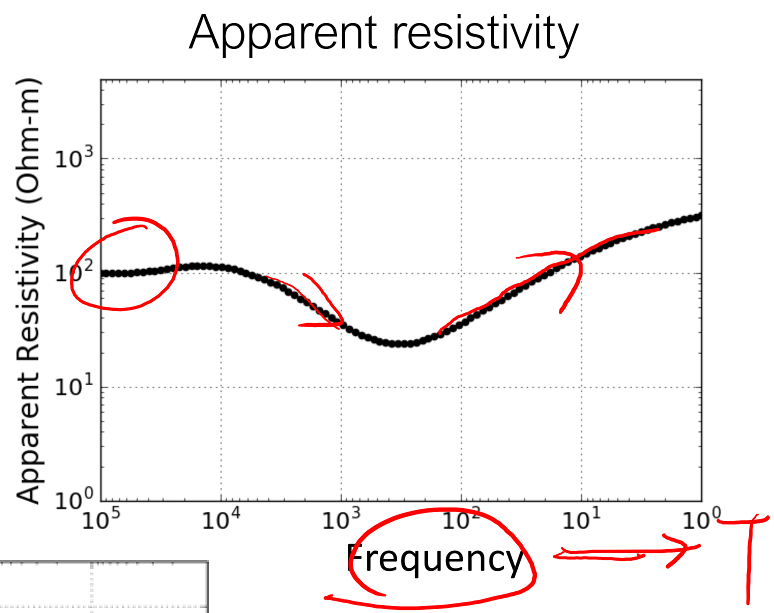
$\phi \approx \frac{\pi}{4}(1 - \frac{\partial \log(\rho_a)}{\partial \log(T)})$, where T is the period of the EM signal

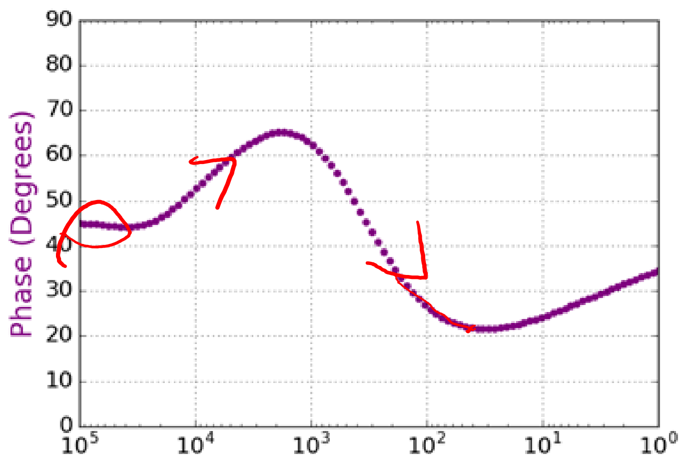
Therefore, if ρ_a increases with T, the derivative term is positive, and the phase $\phi < \frac{\pi}{4}$

If ρ_a decreases with T, the derivative term is negative, and the phase $\phi > \frac{\pi}{4}$

Three layer model: phase



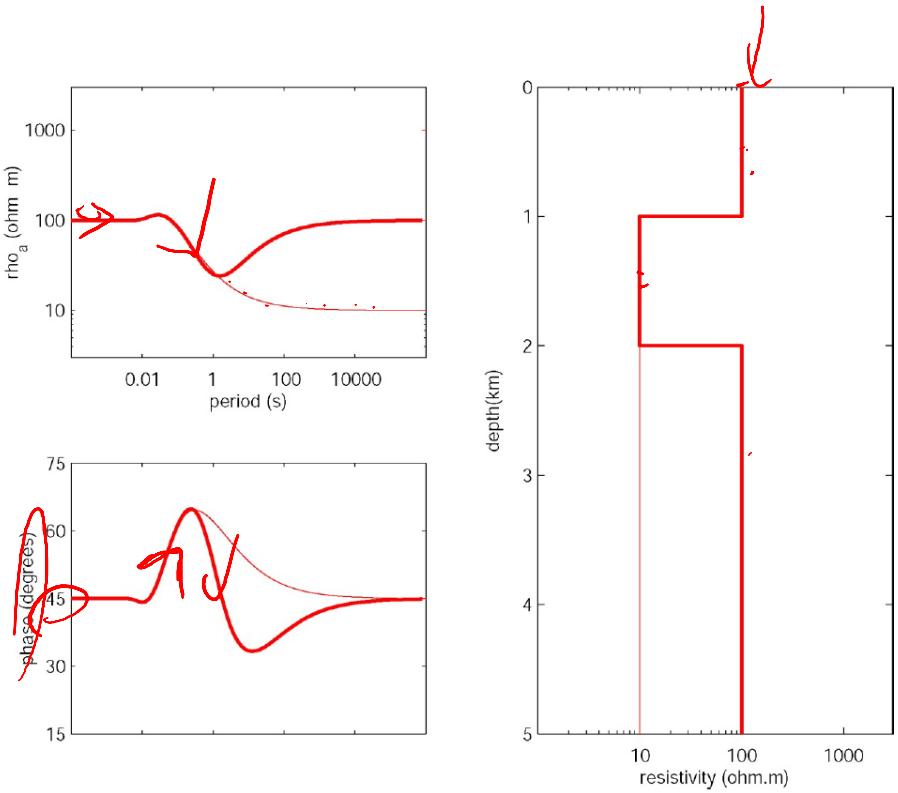




Summary

- MT sounding curve reflects the subsurface resistivity and its change with depth.
  - Higher frequency reflects shallower part
  - Lower frequency reflects deeper part.
- Phase is also sensitive to change in resistivity with depth.
  - When resistivity increases with depth, the phase is smaller than $\frac{\pi}{4}$
  - When resistivity decrease with depth, the phase is larger than $\frac{\pi}{4}$

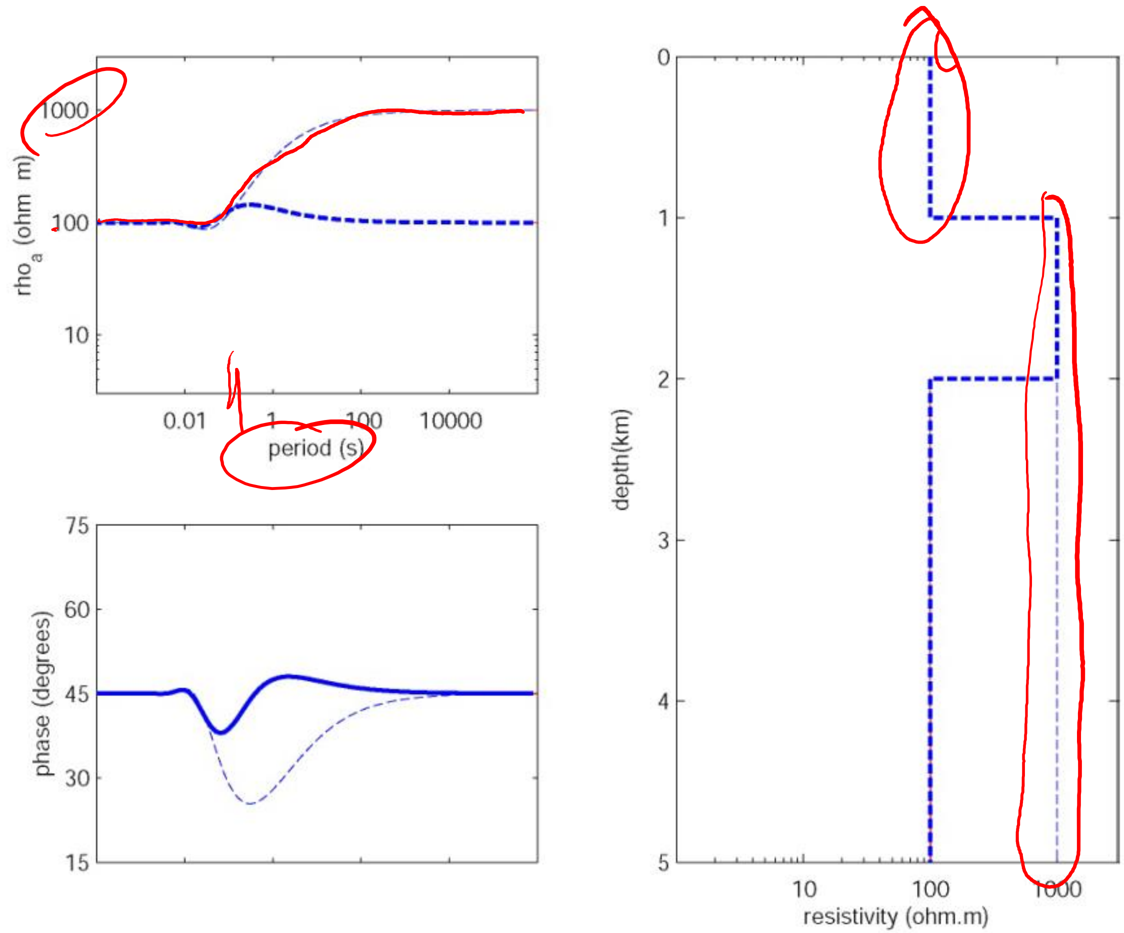
Example 1: Conductive layer in halfspace



- At short periods (T < 0.01 s) the apparent resistivity equals that of the upper layer (100 Ωm)
- At period of T = 0.1 s the apparent resistivity starts to decrease rapidly as the conductive layer (10 Ωm) is detected by the EM signals.
- For the 2 layer model, the apparent resistivity then asymptotes at 10 Ωm at long periods.
- For the 3 layer model the apparent resistivity increases at T > 1 s as the electromagnetic signals enter the third layer (100 Ωm) below 2 km depth.

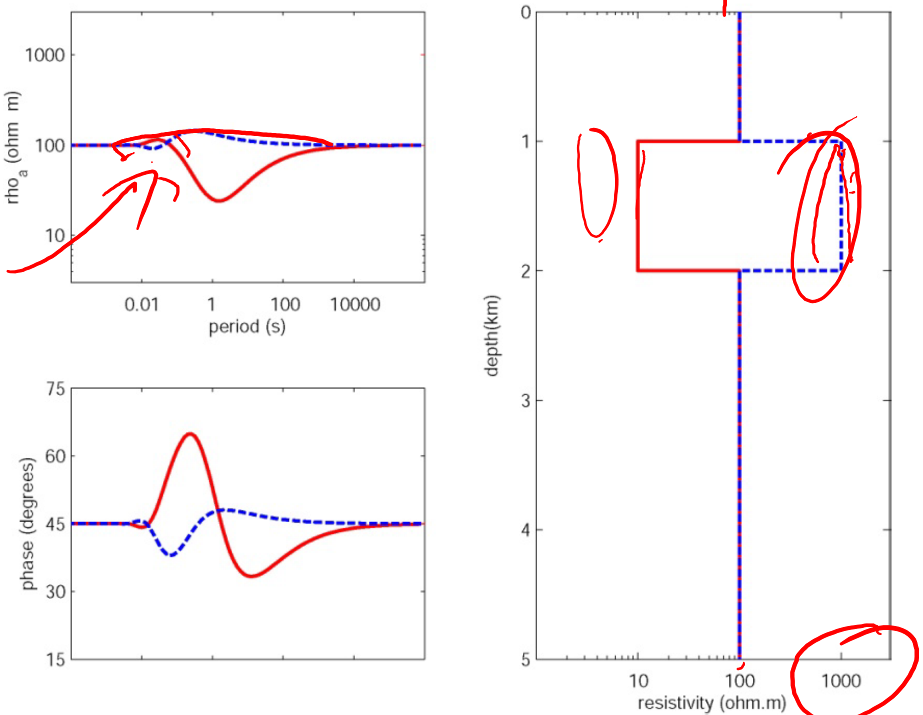
Credit: Martyn Unsworth, University of Alberta, 2013

Example 2: Resistive layer in halfspace



- Similar to previous example, except that the second layer is a resistor.

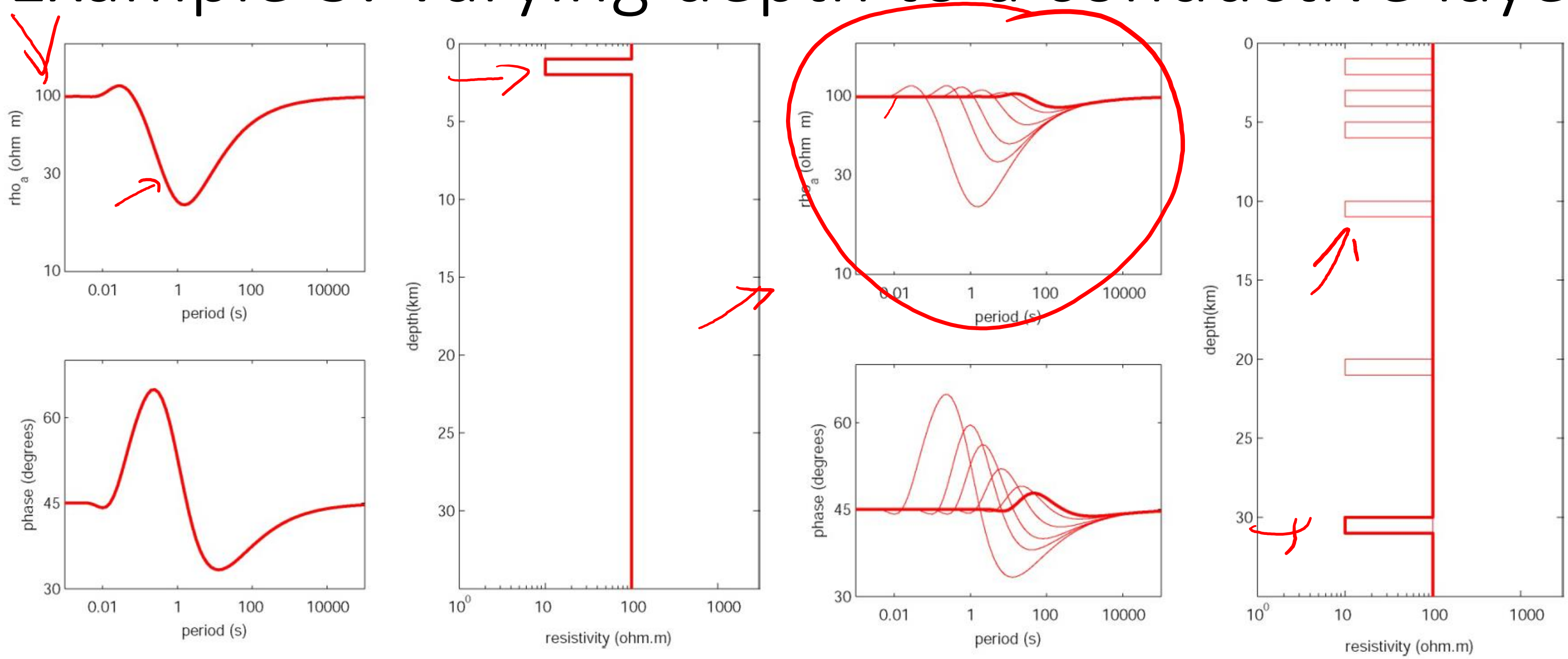
Credit: Martyn Unsworth, University of Alberta, 2013



- second layer with resistivity contrast of 10 compared to the 1st and 3rd layers.
- Effect of second layer is observed at the same period in each case (T = 0.01 s)
- Apparent resistivity at long period is same in each case (T ~ 10000 s)
- Model with conductive second layer has greater effect on apparent resistivity. This is because MT signals are strongly attenuated by the conductor and this makes a significant change at the surface, where the impedance is computed. In contrast, the EM signals travel through the resistive layer with minimal attenuation. Thus the resistive layer does not significantly change the surface impedance.

Credit: Martyn Unsworth, University of Alberta, 2013

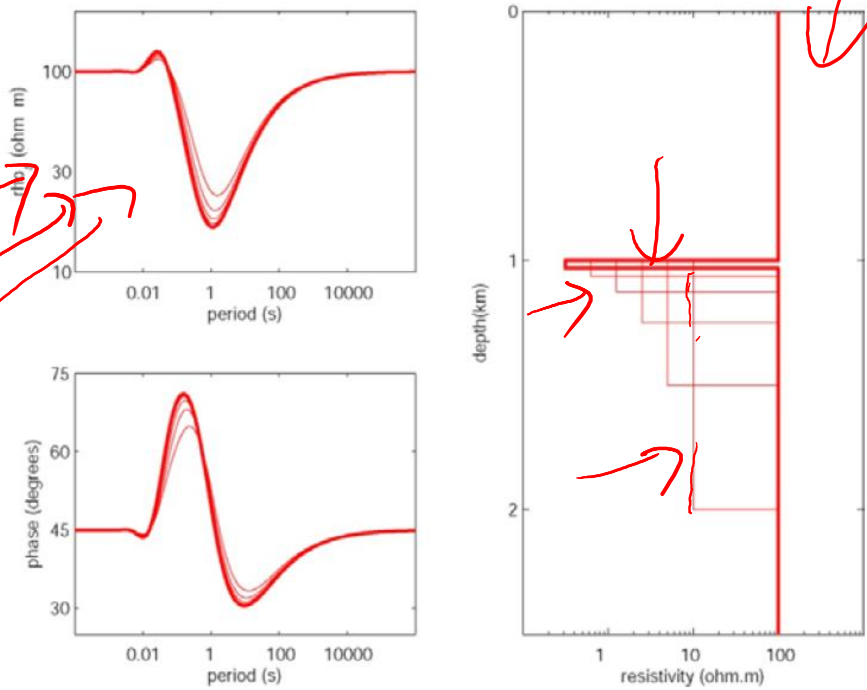
Example 3: Varying depth to a conductive layer



- As depth to the layer increases, the period at which it is detected increases. This is as expected from skin depth.
- The magnitude of the response decreases as the layer becomes deeper. This is because the apparent resistivity represents an **average resistivity** from the surface to the maximum depth of exploration.
- MT is good at determining the depth of a conductive layer.

Credit: Martyn Unsworth, University of Alberta, 2013

Example 4: Layer of constant conductance

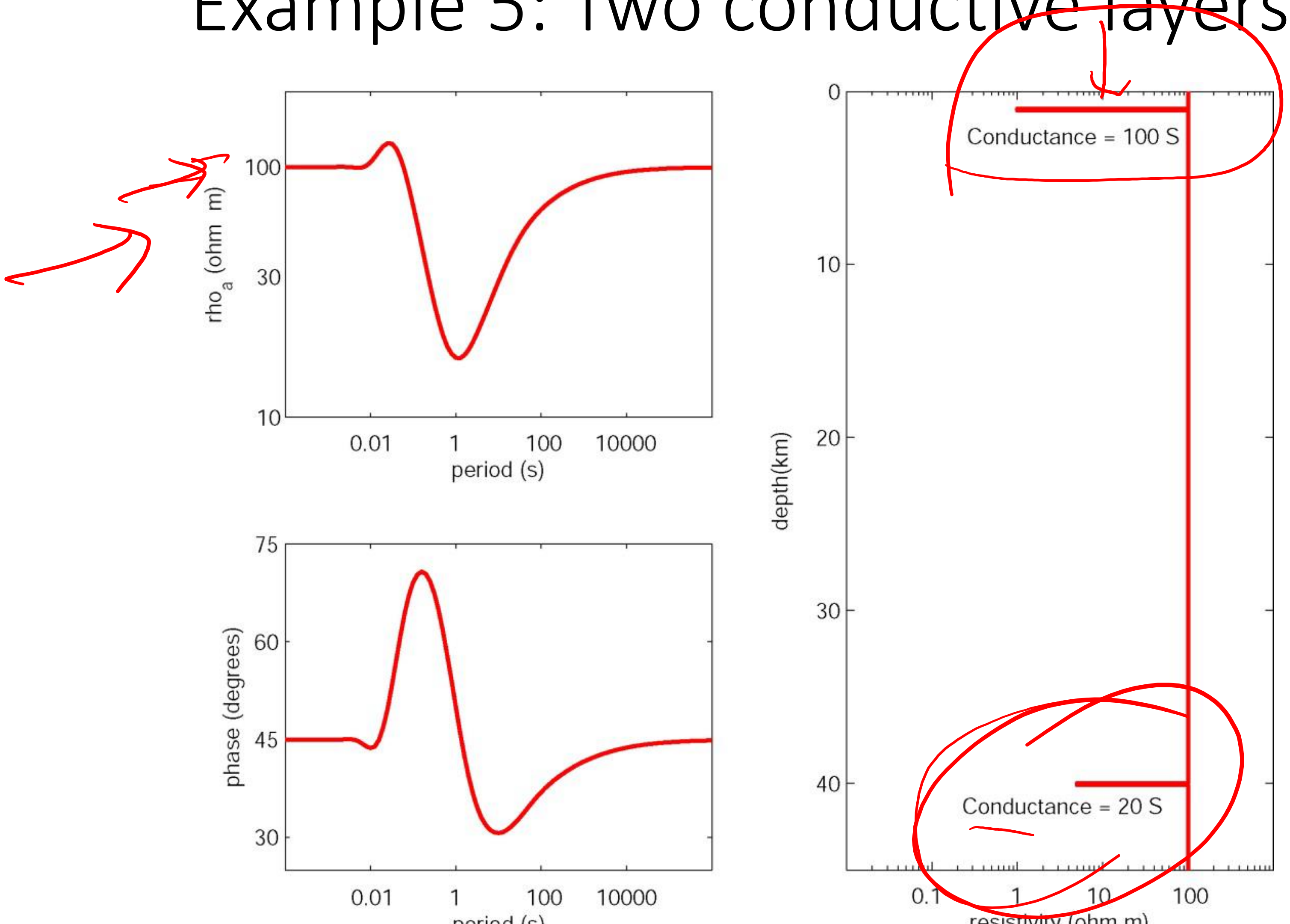


- Addition information, such as constraints from other geophysical methods, rock properties or well logs must be used to overcome this non-uniqueness.
- Note that for the surface layer, resistivity and thickness can be individually determined. The apparent resistivity at the highest frequency will be the true resistivity (provided that the highest frequency is high enough).

- Conductance of a layer is the **product of conductivity and thickness**
- Each model has a layer with conductance 100 Siemens.
- Once the layer become **thin** (compared to it's depth), the MT curves for different combinations of thickness and conductivity cannot be distinguished.
- This is an example of **non-uniqueness**. MT cannot separately determine the thickness and resistivity of the layer. Only the conductance can be determined.

Credit: Martyn Unsworth, University of Alberta, 2013

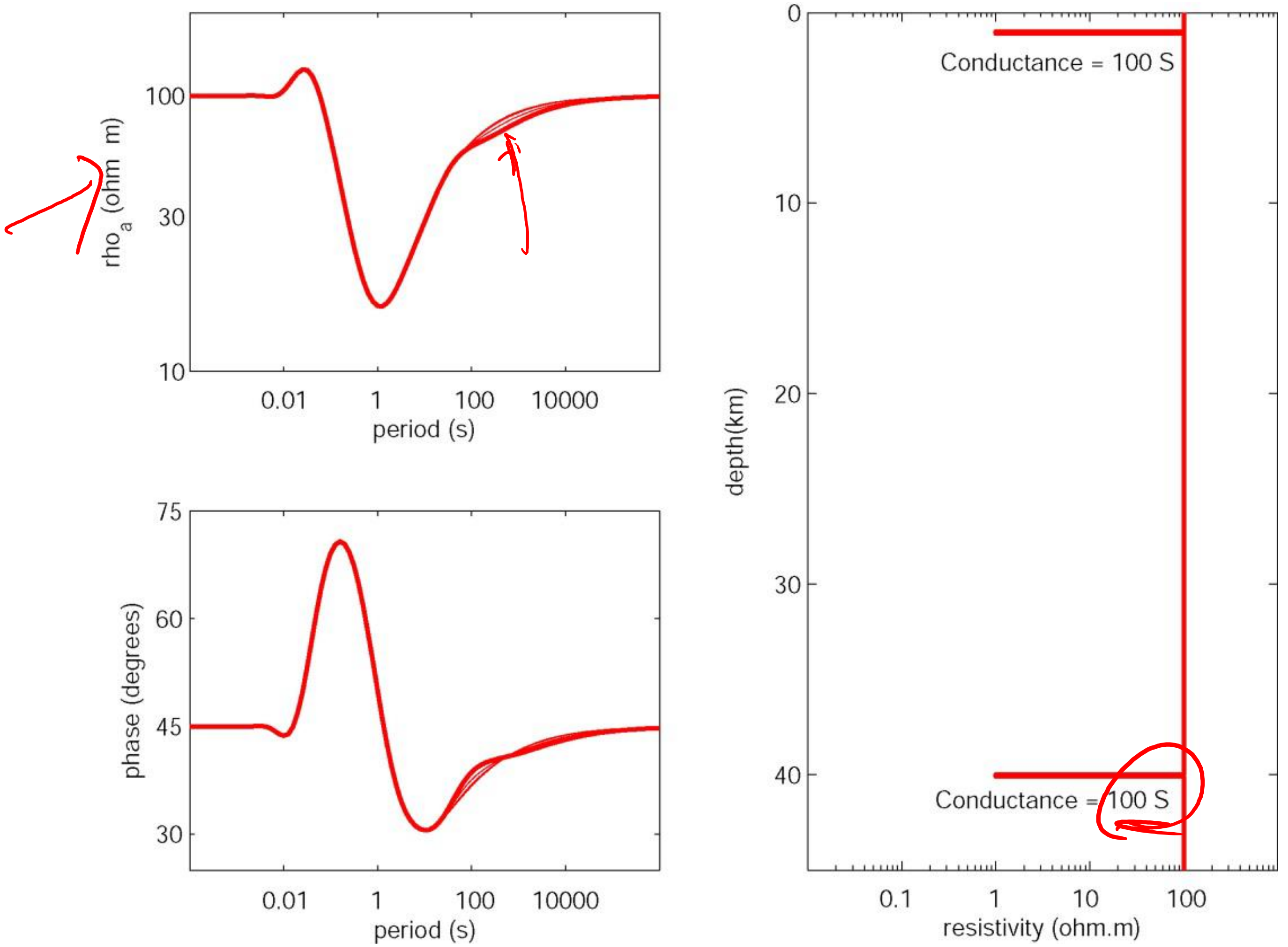
Example 5: Two conductive layers



Upper layer has a conductance of 100 S, while the lower layer has a variable conductance.

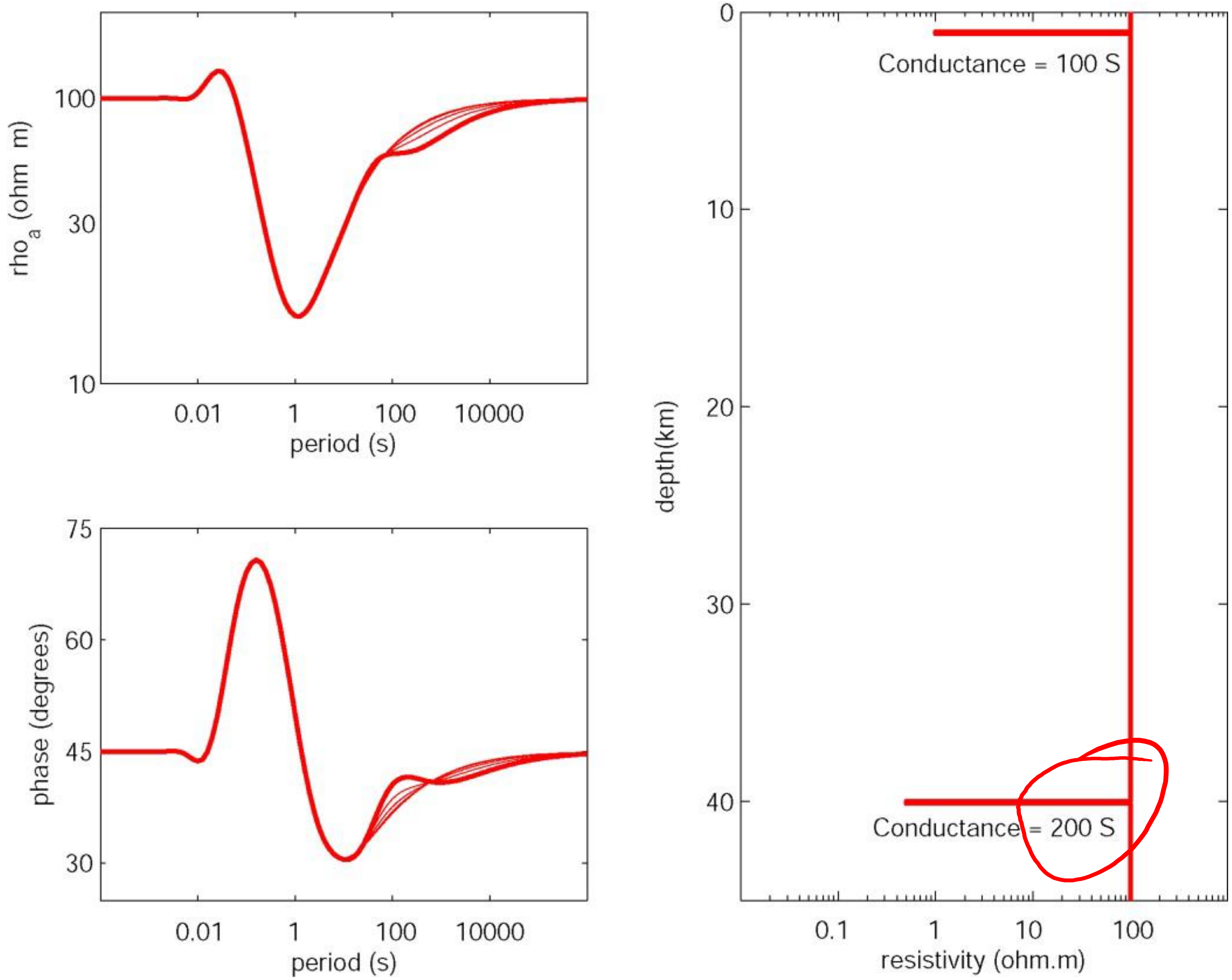
Credit: Martyn Unsworth, University of Alberta, 2013

Example 5: Two conductive layers



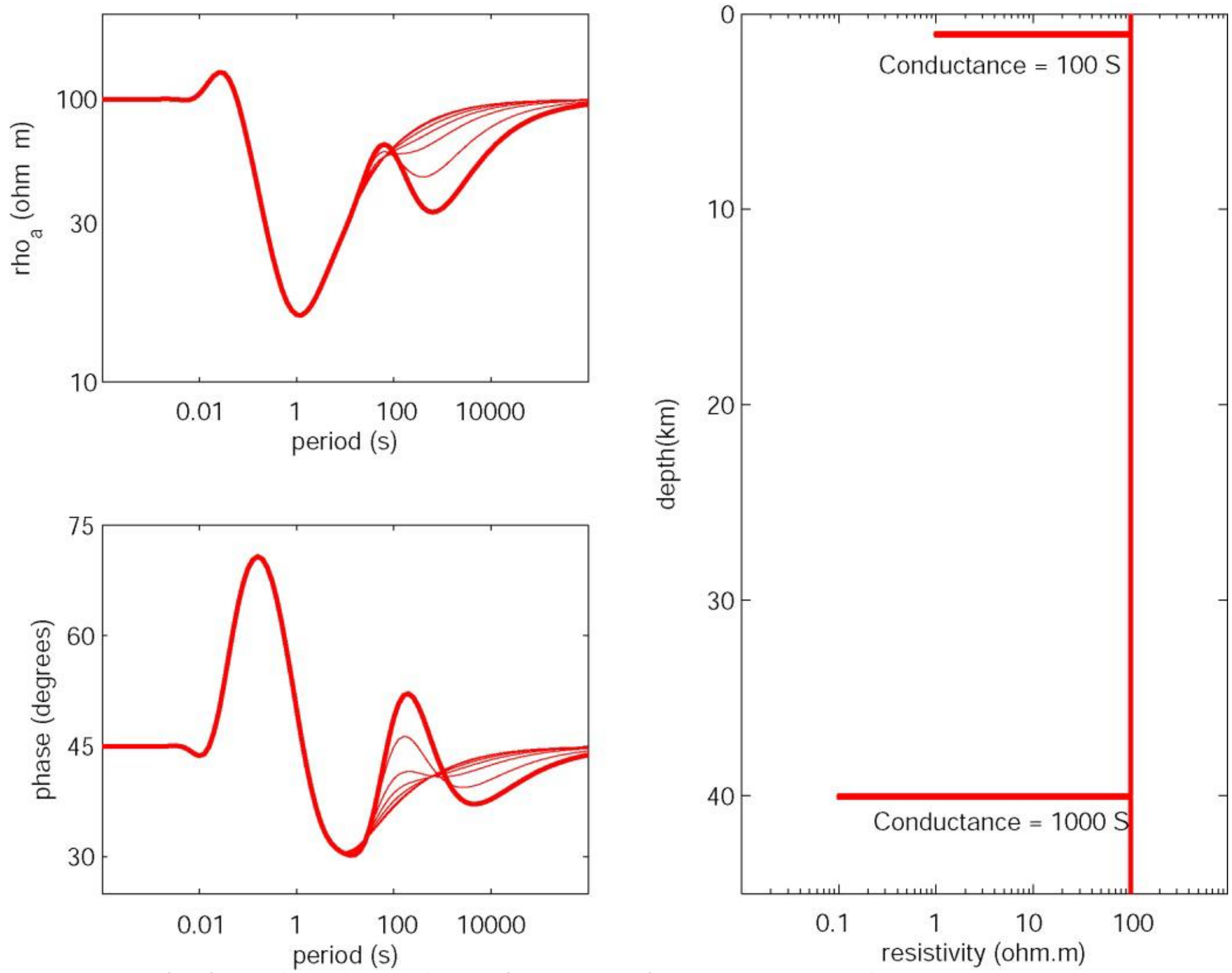
Credit: Martyn Unsworth, University of Alberta, 2013

Example 5: Two conductive layers



Credit: Martyn Unsworth, University of Alberta, 2013

Example 5: Two conductive layers



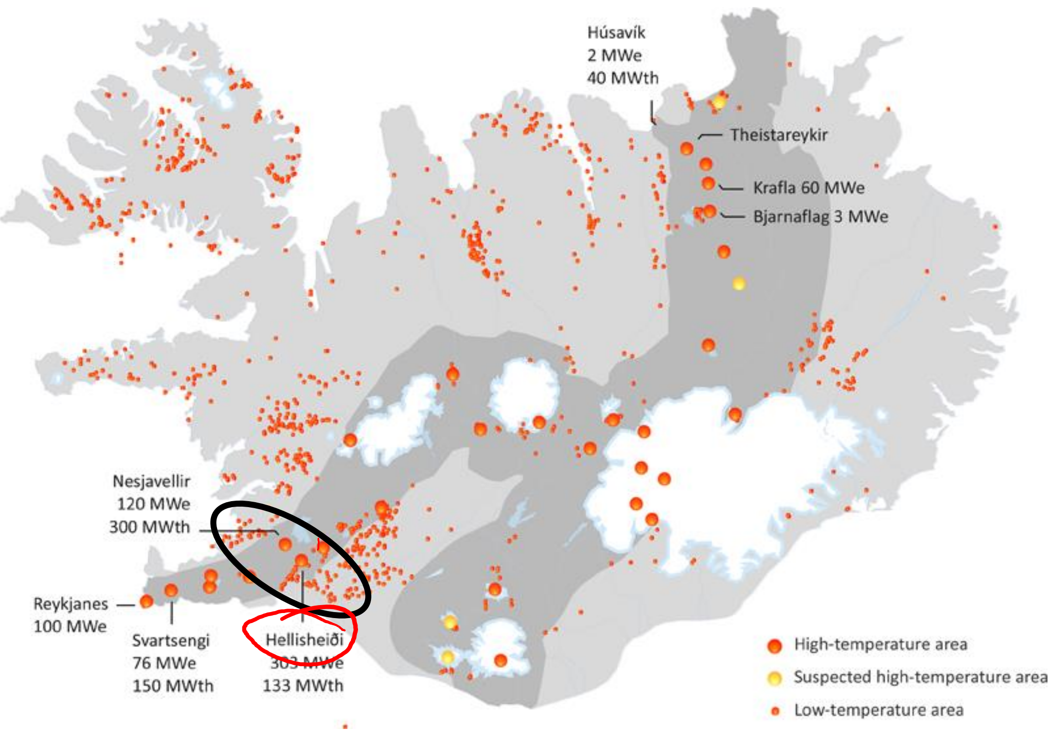
The lower layer can only be detected with MT when its **conductance is greater** than that of the upper layer.

Credit: Martyn Unsworth, University of Alberta, 2013

Hengill geothermal region: setup

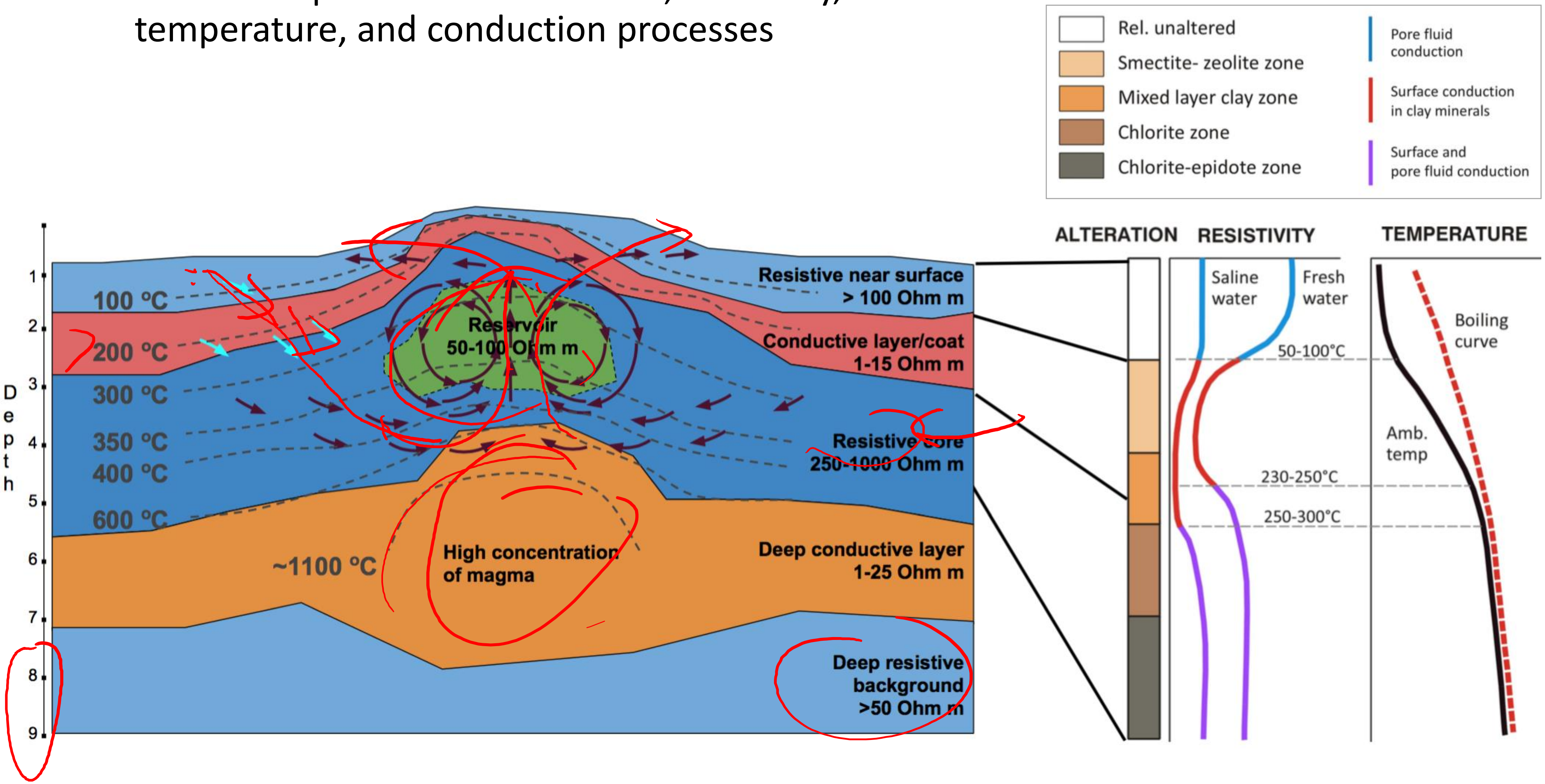
- Iceland: geothermal hot spot
  - On the mid-Atlantic ridge
  - Hosts multiple high temperature geothermal systems

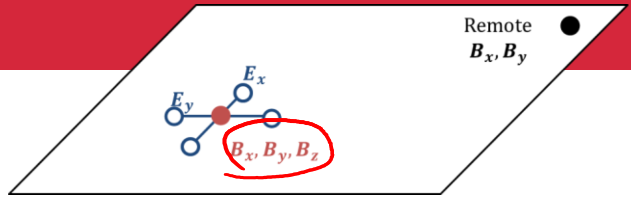
- Hengill geothermal area
  - Supplies majority of hot water in Reykjavik
  - Contributes ~450 Mwe to National power grid



Physical properties

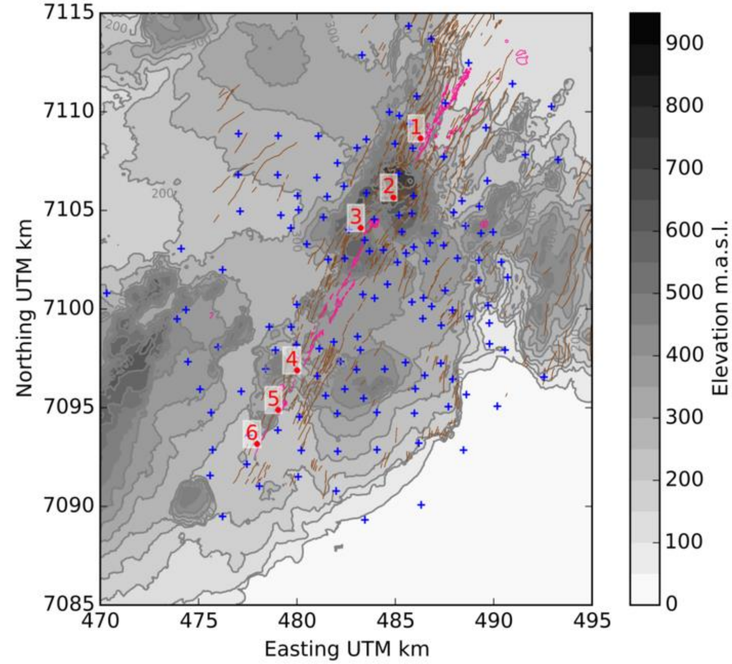
- Relationships between alteration, resistivity, temperature, and conduction processes





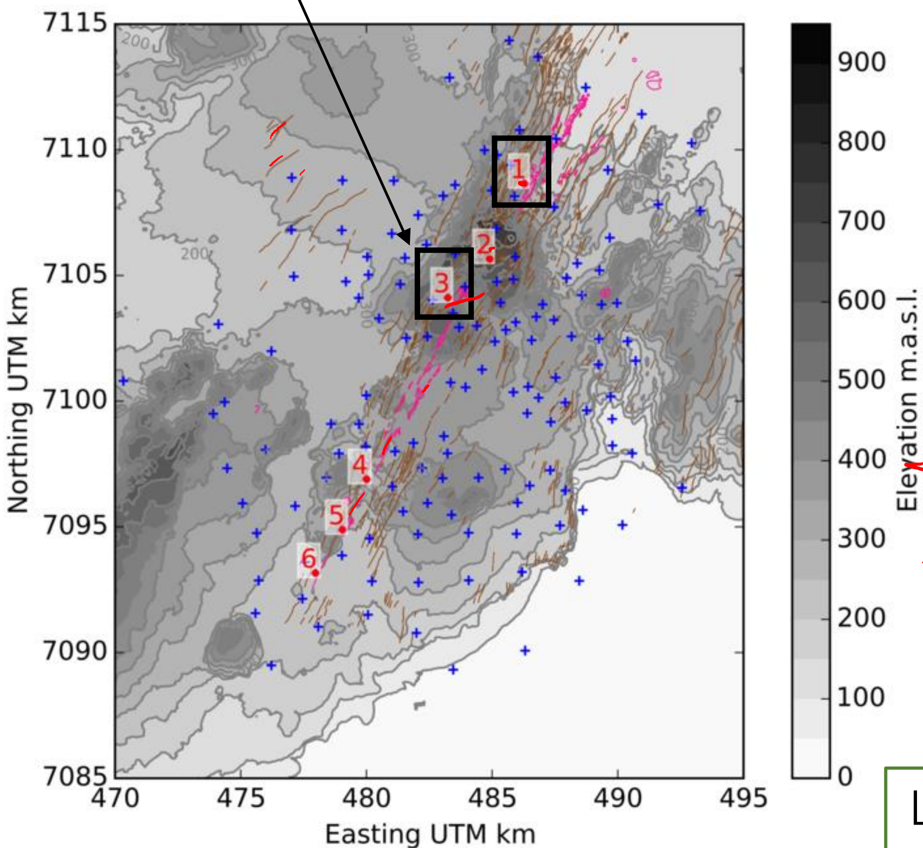
Survey

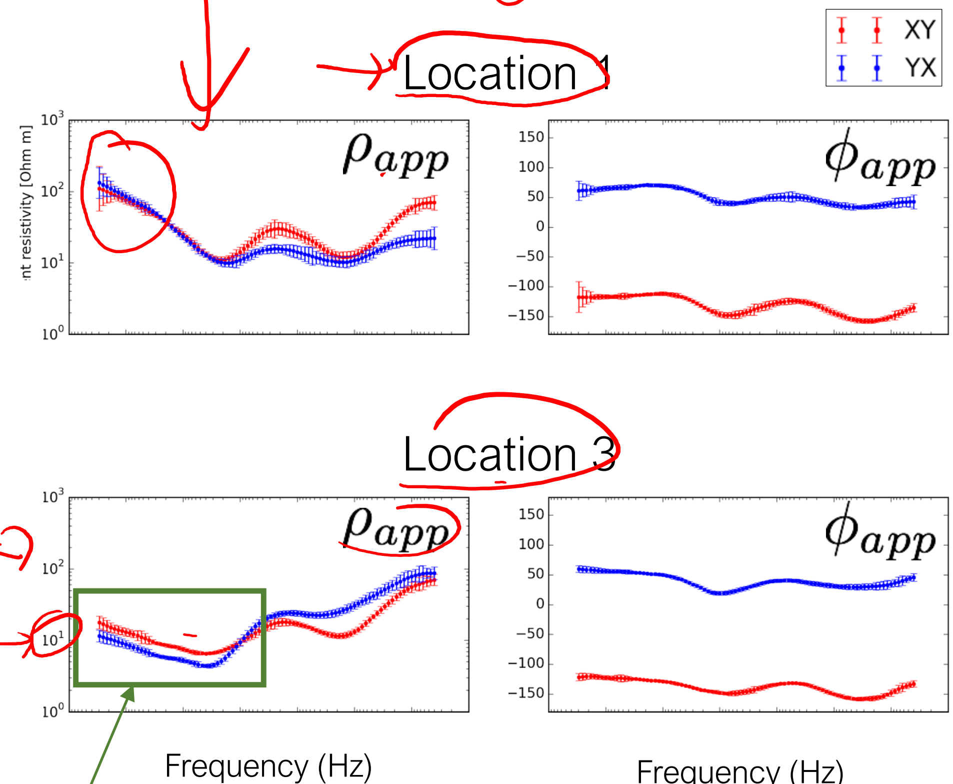
- MT instrumentation
  - Phoenix MTU5's
- Survey
  - 133 stations used
  - Combination of 2E and 2E+3H setup
  - Frequencies: 300 – 0.001 Hz
- Remote reference
  - About 40 km away
- Raw data processing using Phoenix software



Data

Surface alteration, hot water, fumaroles

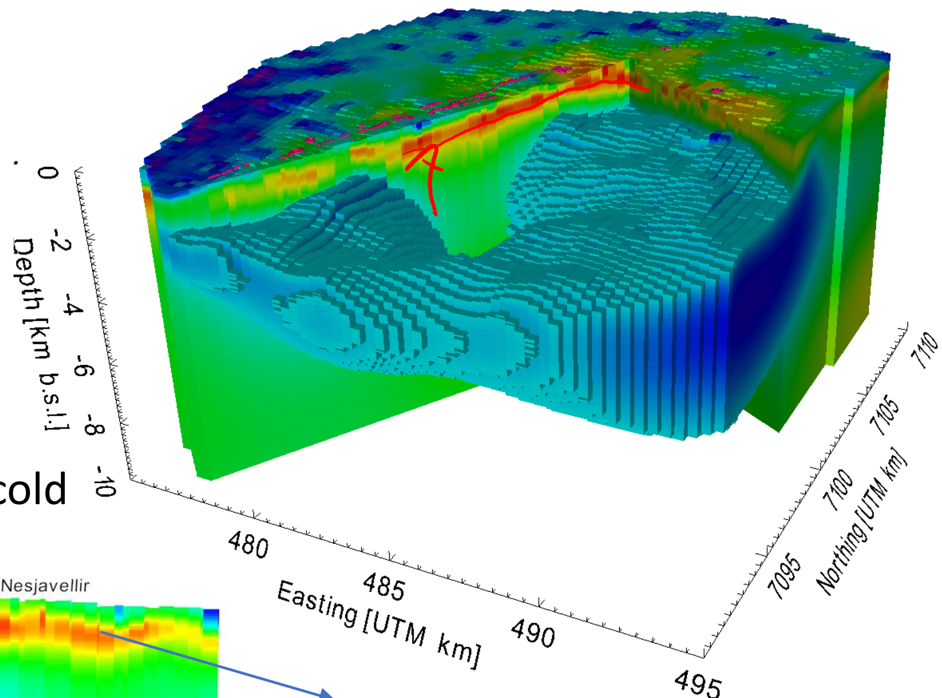




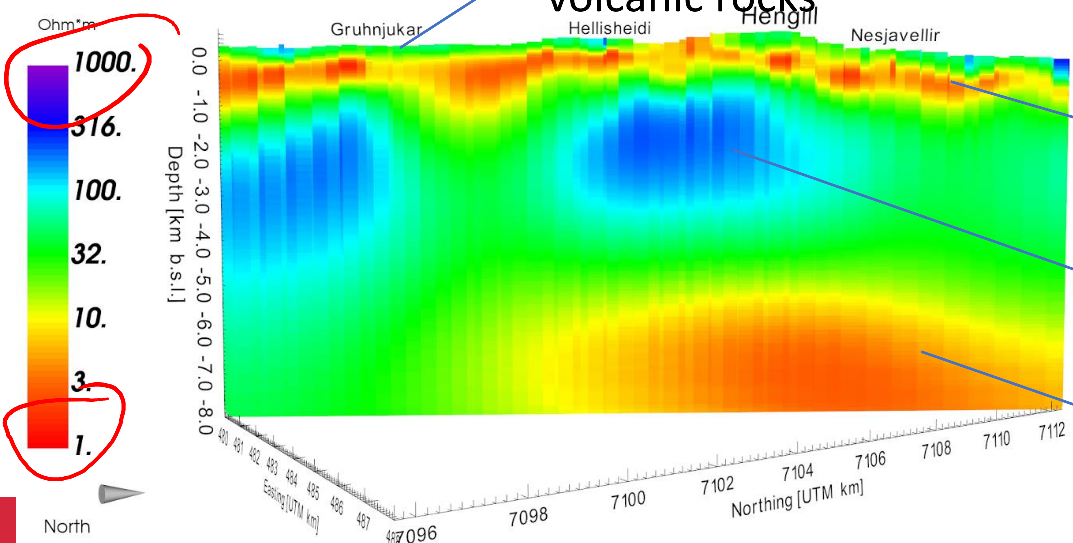
Low apparent resistivity

3D inversion

- Off-diagonal impedance (Z_{xy} and Z_{yx}) used
- Combined multi-frequency inversion (300 Hz – 0.001 Hz)



Unaltered and cold volcanic rocks



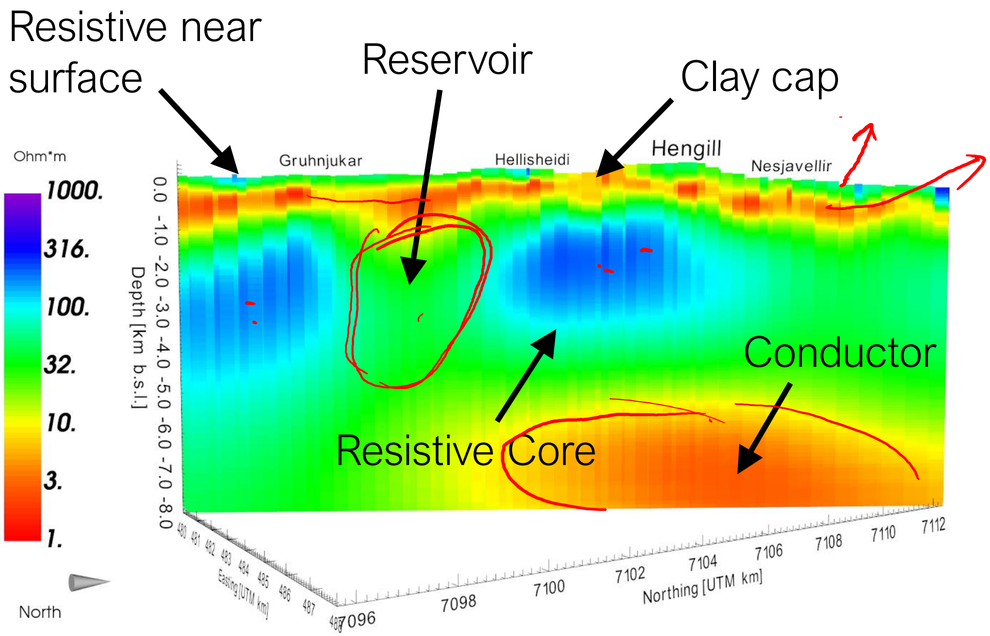
Smectite and zeolite hydrothermal alteration

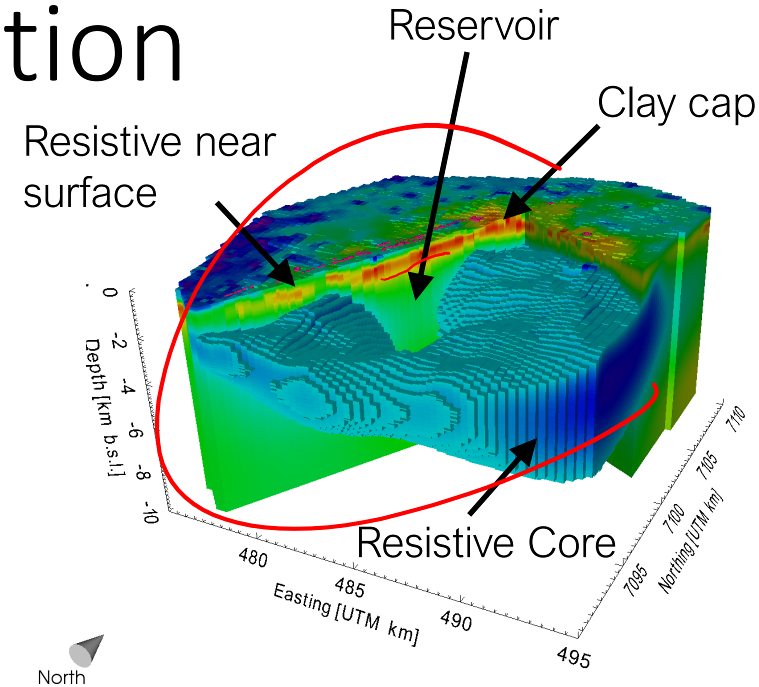
Chlorite and epidote alteration

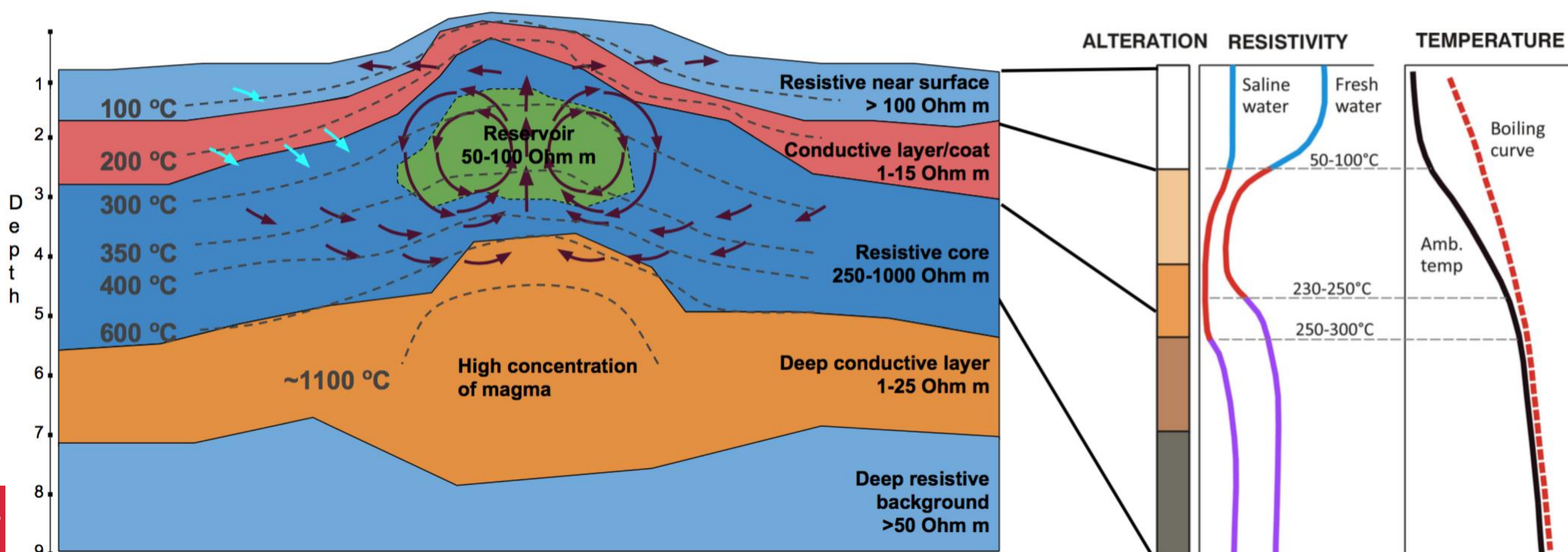
Heat source

Rosenkjaer et al, 2015

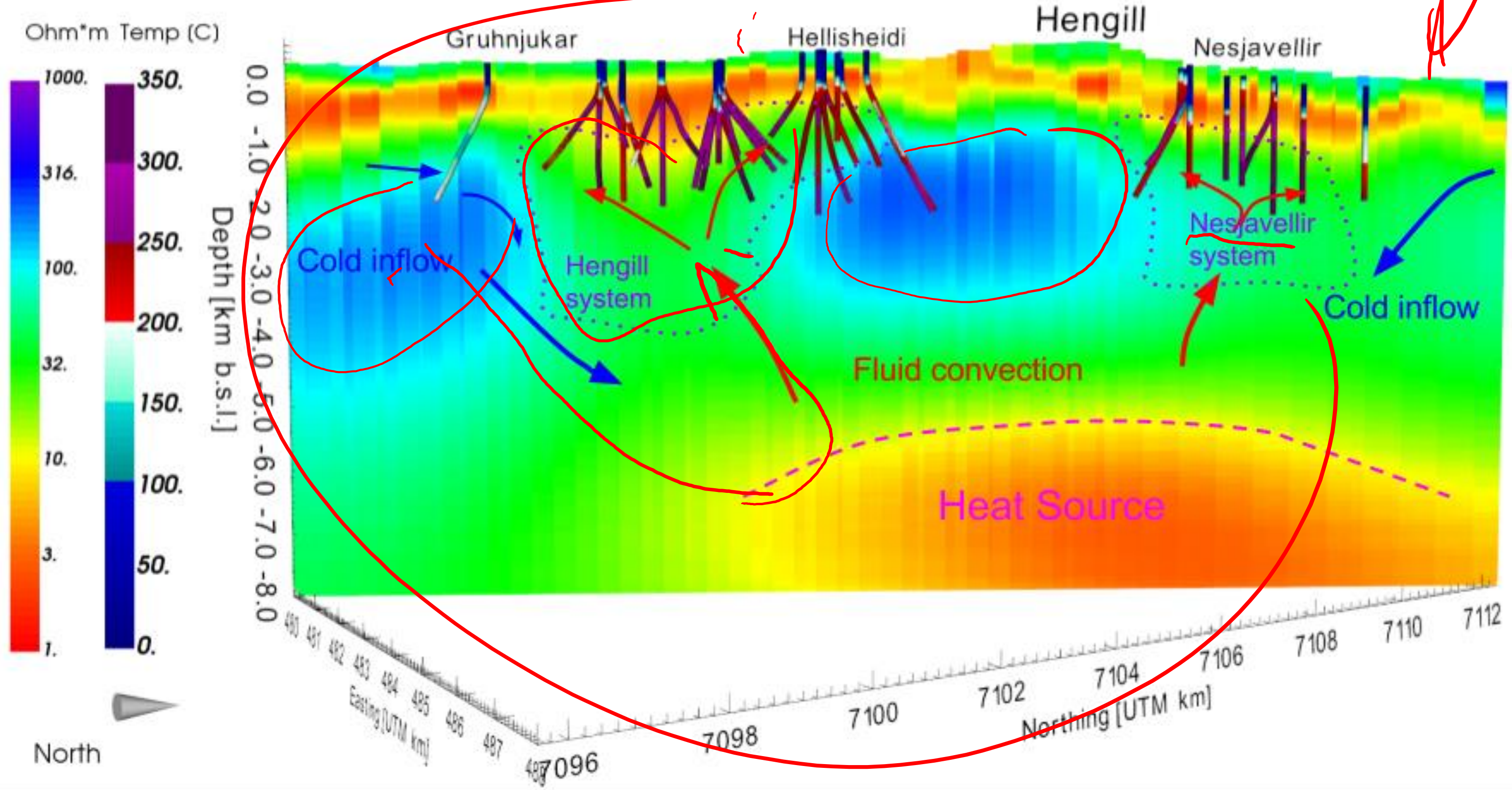
Interpretation







Synthesis



- Conductive layer corresponds with formation temperature
- Two main production fields: Hengill and Nesjavellir
- Deep conductive heat source

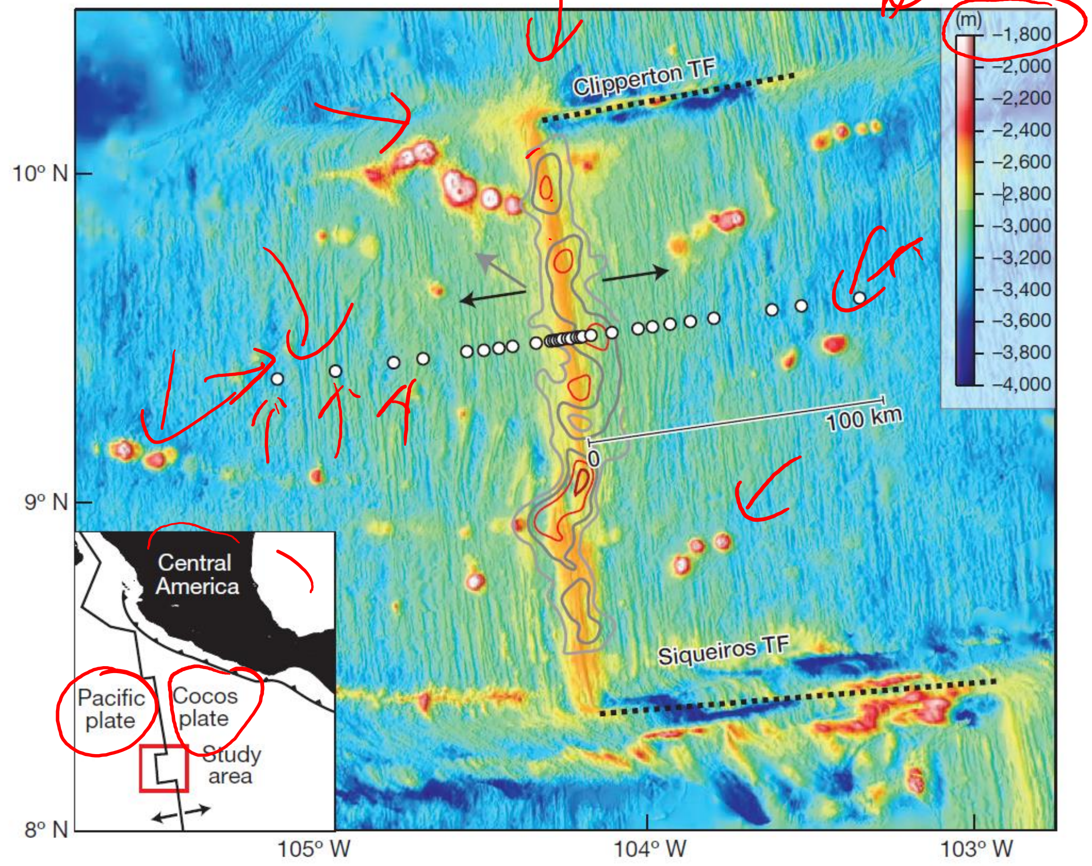
Electrical image of passive mantle upwelling beneath the northern East Pacific Rise

Kerry Key et al., 2013, Nature

Motivation

- Melt generated by mantle upwelling is fundamental to the creation of new oceanic crust at mid-ocean ridges
- Yet forces controlling this process are debated.
- Passive-flow models
    - Predict symmetric upwelling due to viscous drag from diverging tectonic plates
    - However, asymmetric upwelling observed which suggests anomalous mantle pressure and temperature gradients
- Active models
    - Observations of concentrated upwelling centers
    - Buoyancy forces give rise to convective flow

Study area



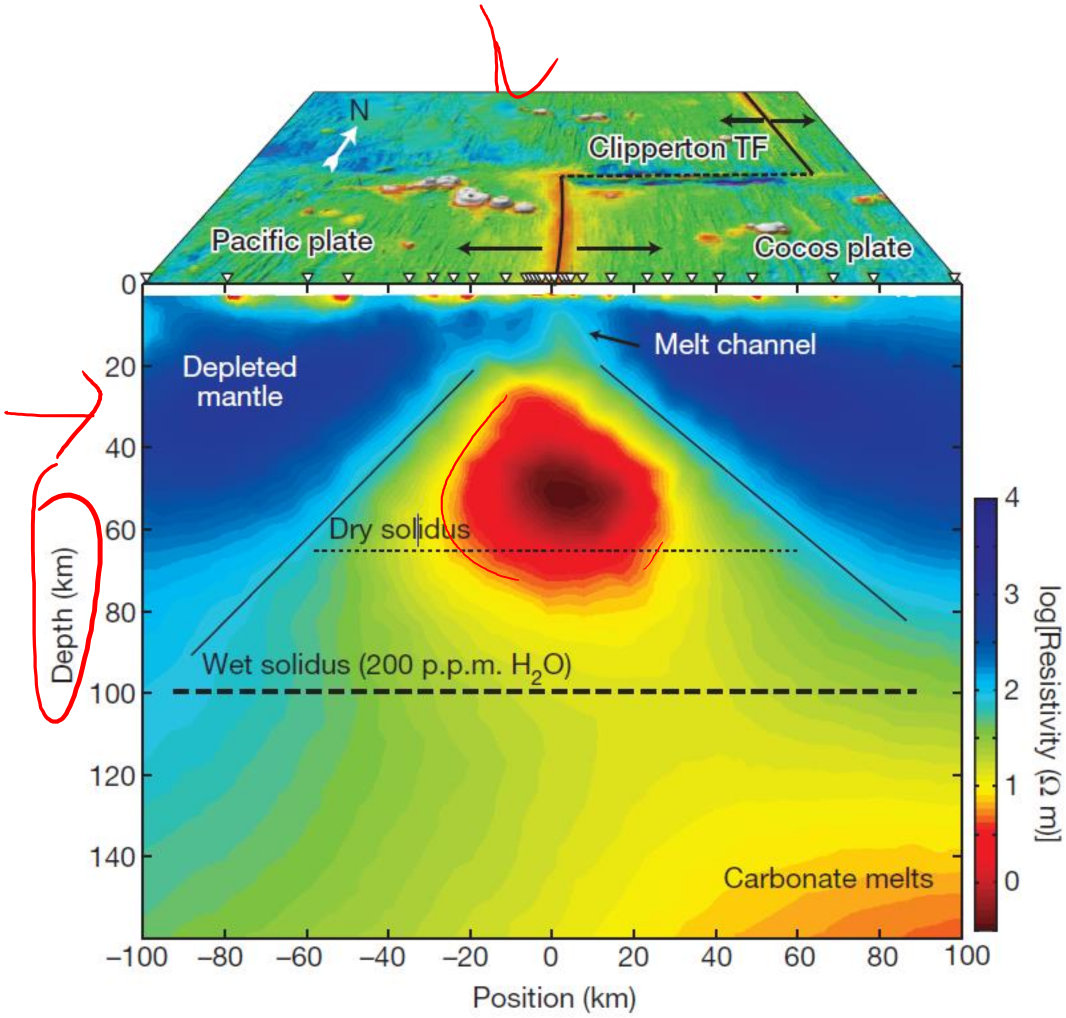
Location of the magnetotelluric survey across the fast spreading East Pacific Rise. Twenty-nine sea-floor magnetotelluric stations (white circles) were deployed across the ridge axis.

MT data collection

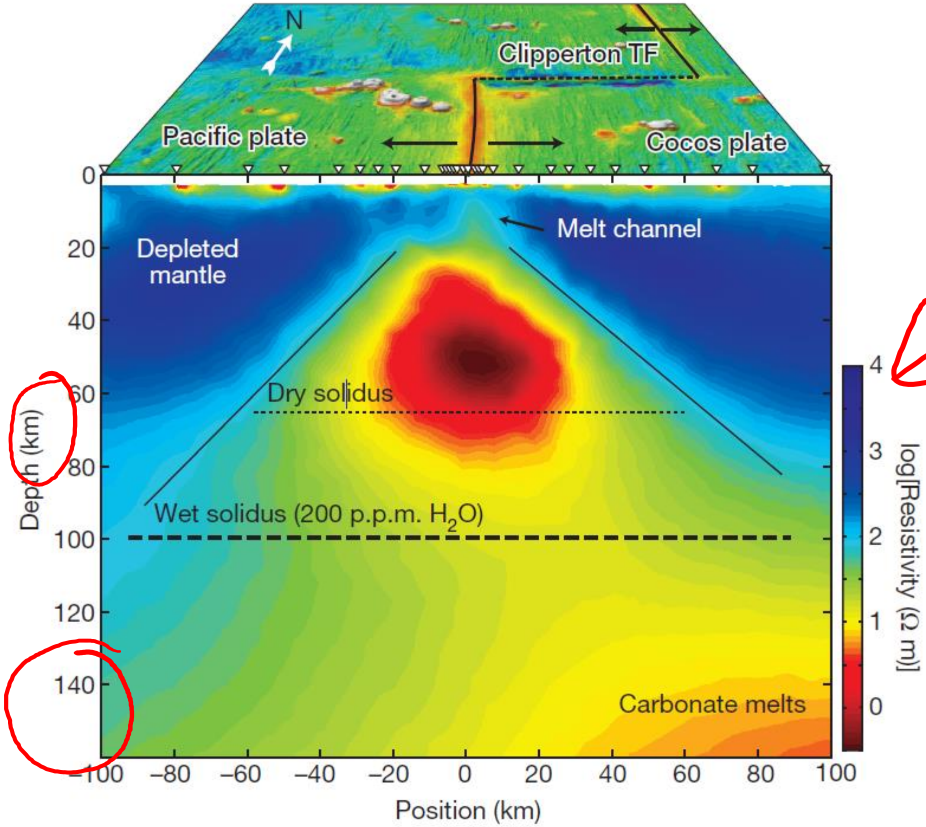
- broadband magnetotelluric instrumentation that is sensitive to the high frequencies required to constrain the shallow mantle and that requires only 10–20 days of recording time

- 200-km profile of 29 magnetotelluric stations

MT resistivity model



- Magnetotelluric resistivity image of mantle upwelling beneath the East Pacific Rise.
- Green to red colours indicate high conductivity (low resistivity) due to partial melts generated in the upwelling mantle.



Interpretations

- Our data reveal a symmetric, high conductivity region at depths of 20–90 kilometres that is consistent with partial melting of passively upwelling mantle9–11.
- The triangular region of conductive partial melt matches passive-flow predictions.
- We interpret the mantle electrical structure as evidence that plate-driven passive upwelling dominates this ridge segment, with dynamic forces being negligible.