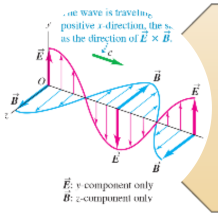
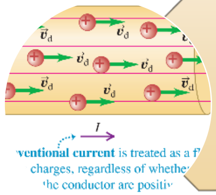
Imaging Earth through electromagnetic (EM) signatures

Florence Ramirez

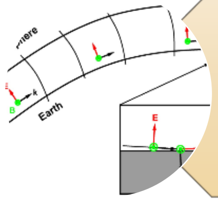
GEO-DEEP9300 01.Nov.2021



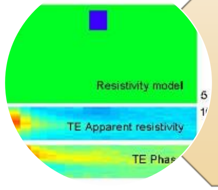
What is EM wave?



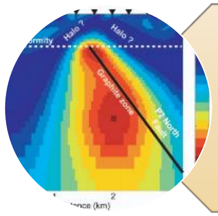
EM - matter interaction: What can we infer?



EM methods: overview



How MT measures and infers Earth's property?



MT Analysis: Subsurface imaging and inferences

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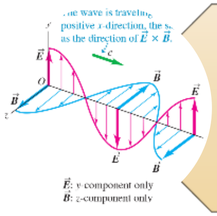

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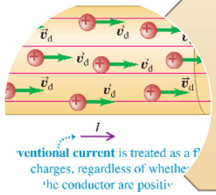

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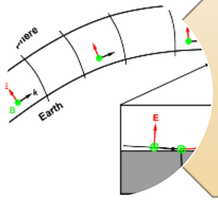

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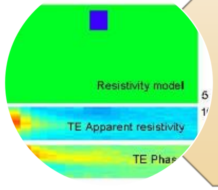

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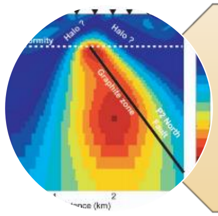
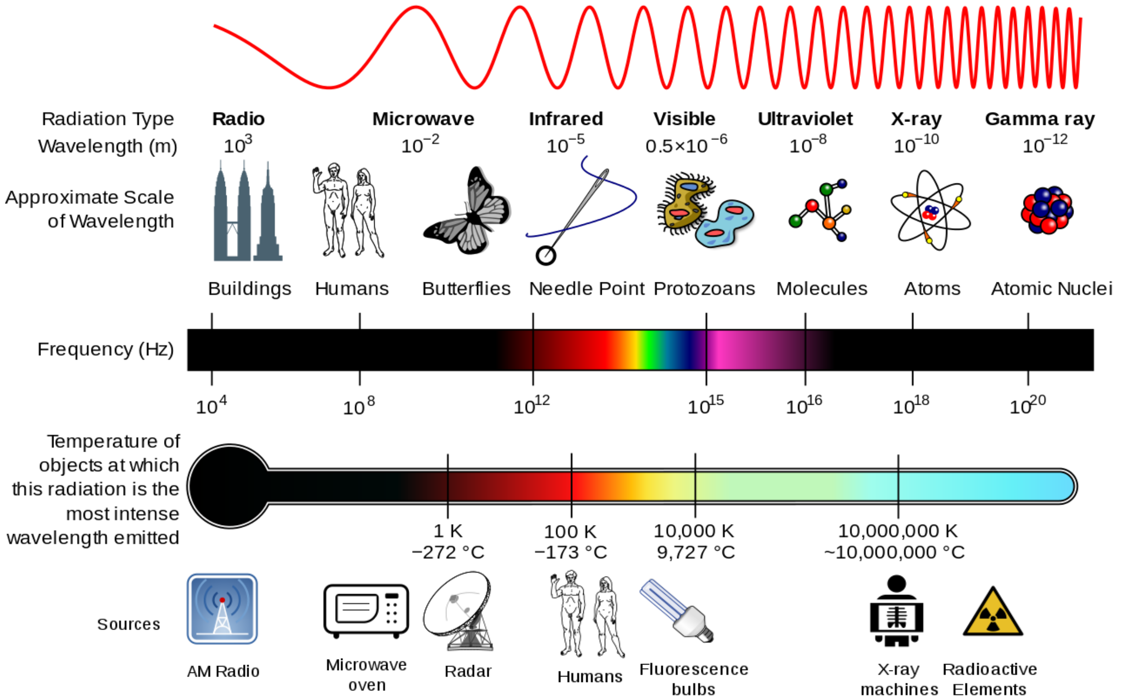


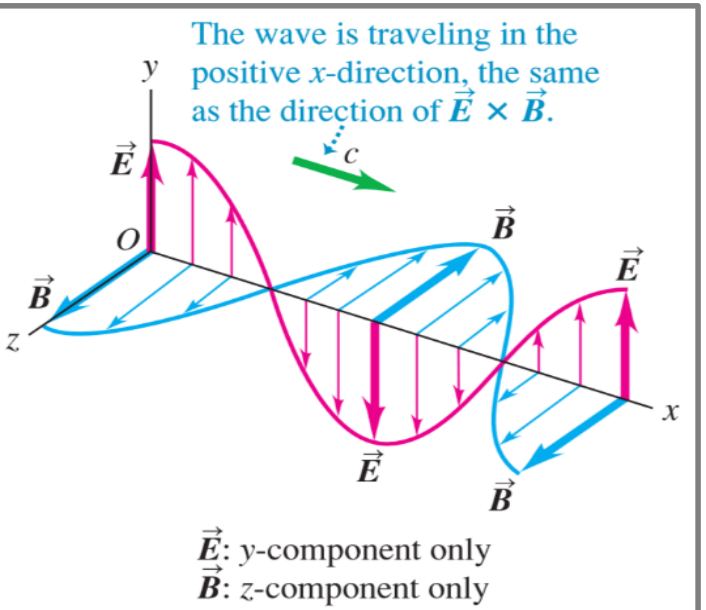
MT Analysis: Subsurface imaging and inferences

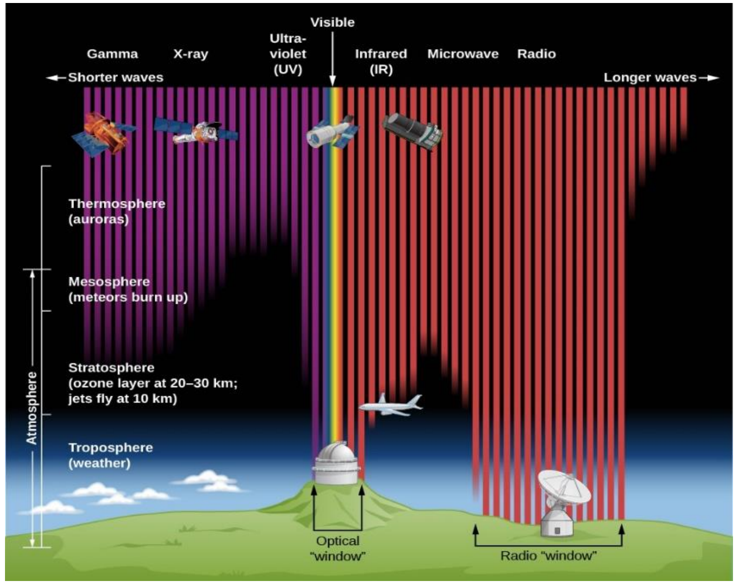
EM wave is…

- a unification of electricity and magnetism (described by *Maxwell's equations*)
- composed of **E** and **B** fields that can sustain each other
- a time-varying magnetic field (**B**) acts a source of electric field (**E**), and time-varying **E** field acts as a source of **B** field



https://no.m.wikipedia.org/wiki/Fil:EM_Spectrum_Properties_edit.svg





https://courses.lumenlearning.com/astronomy/chapter/the-electromagnetic-spectrum/

Maxwell's Equations

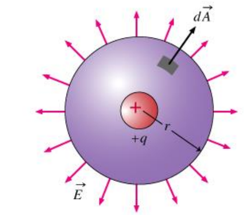
E – electric field strength
B – induced magnetic field
I – electric current
J – current density
Φ_E - electric flux
Φ_B - magnetic flux
Q_{encl} - enclosed electric charge
ϵ_0 - electric permittivity in free surface
μ_0 - magnetic permeability in free surface

Integral Form ***Differential Form***

$$\oint \boldsymbol{E}\cdot d\boldsymbol{A} = \Phi_E = \frac{Q_{\text{encl}}}{\epsilon_0}$$

Gauss's Law

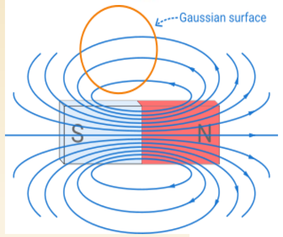
$$\nabla\cdot\mathbf{E} = \frac{Q_{\text{encl}}}{\epsilon_0}$$



$$\oint \boldsymbol{B}\cdot d\boldsymbol{A} = 0$$

Gauss's law

$$\nabla\cdot\mathbf{B} = 0$$



$$\oint \boldsymbol{B}\cdot d\boldsymbol{l} = \mu_0\left(I+\epsilon_0\frac{d\Phi_E}{dt}\right)_{\text{encl}}$$

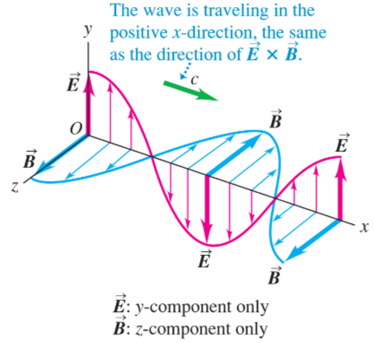
Ampere's law

$$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J}+\epsilon_0\frac{d\mathbf{E}}{dt}\right)$$

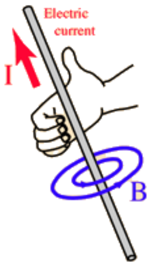
$$\oint \boldsymbol{E}\cdot dl = -\frac{d\Phi_B}{dt}$$

Faraday's law

$$\nabla\times\mathbf{E} = -\frac{d\mathbf{B}}{dt}$$

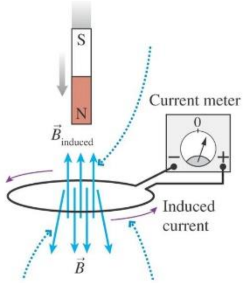

The wave is traveling in the positive x-direction, the same as the direction of $\vec{E}\times\vec{B}$.

$\vec{E}$: y-component only
$\vec{B}$: z-component only



Magnetic field from a long straight wire.

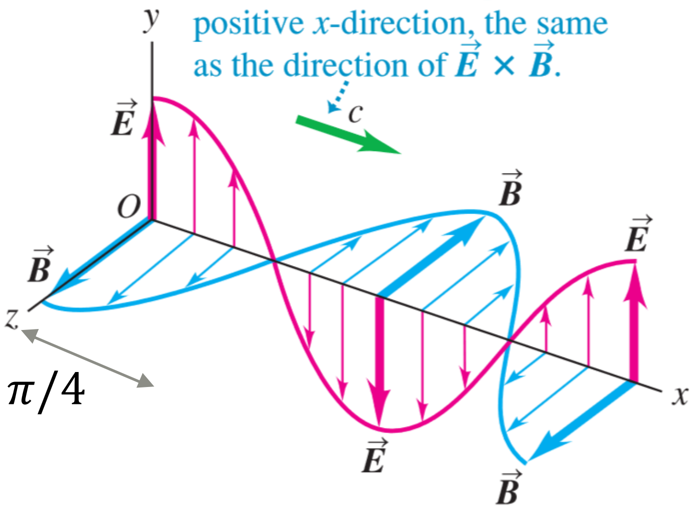
time-varying **E** field acts as a source of **B** field



time-varying **B** field acts as a source of **E** field

KEY properties of EM waves

- EM wave is transverse; **E** and **B** are perpendicular to the direction of the propagation of wave. Both fields are perpendicular with each other.
- There is a definite ratio between the magnitudes of **E** and **B**: $E = cB$.
- The wave travels in a <u>vacuum</u> with a definite and unchanging speed.
- **E** and **B** are ***in-phase*** in free space (phase angle of $\pi/4$)
- EM wave does not require a medium.



The wave is traveling in the positive x-direction, the same as the direction of $\vec{E} \times \vec{B}$.

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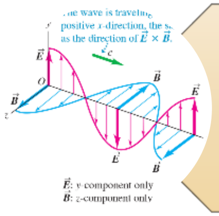
What if there is a MEDIUM?



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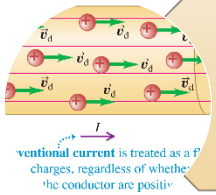

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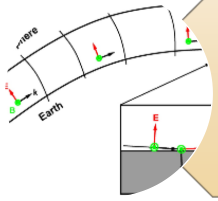
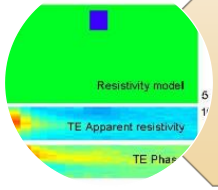


EM methods: overview



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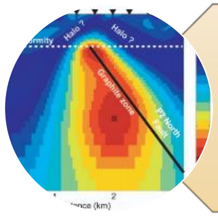

MT Analysis: Subsurface imaging and inferences

Maxwell's equations for a medium

$$\nabla \cdot \mathbf{E} = \frac{Q_{\text{encl}}}{\epsilon}$$ Gauss's Law

$$\nabla \cdot \mathbf{B} = 0$$ Gauss's law

$$\nabla \times \mathbf{B} = \mu\left(\mathbf{J} + \epsilon \frac{d\mathbf{E}}{dt}\right)$$ Ampere's law

$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$$ Faraday's law

E – electric field strength
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J – current density
Q_{encl} - enclosed electric charge
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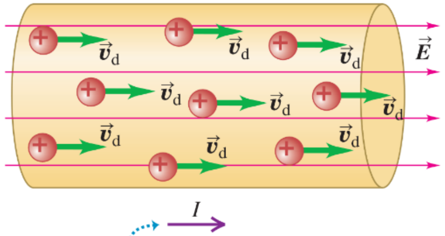
conductor

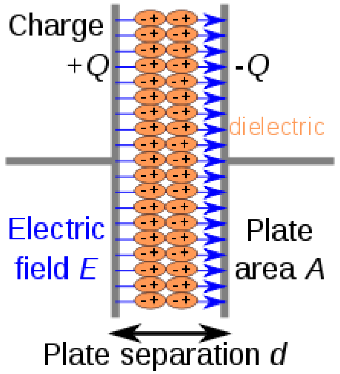


$$\mathbf{J} = \sigma \mathbf{E}$$

$$\sigma \downarrow$$

conductivity

dielectric

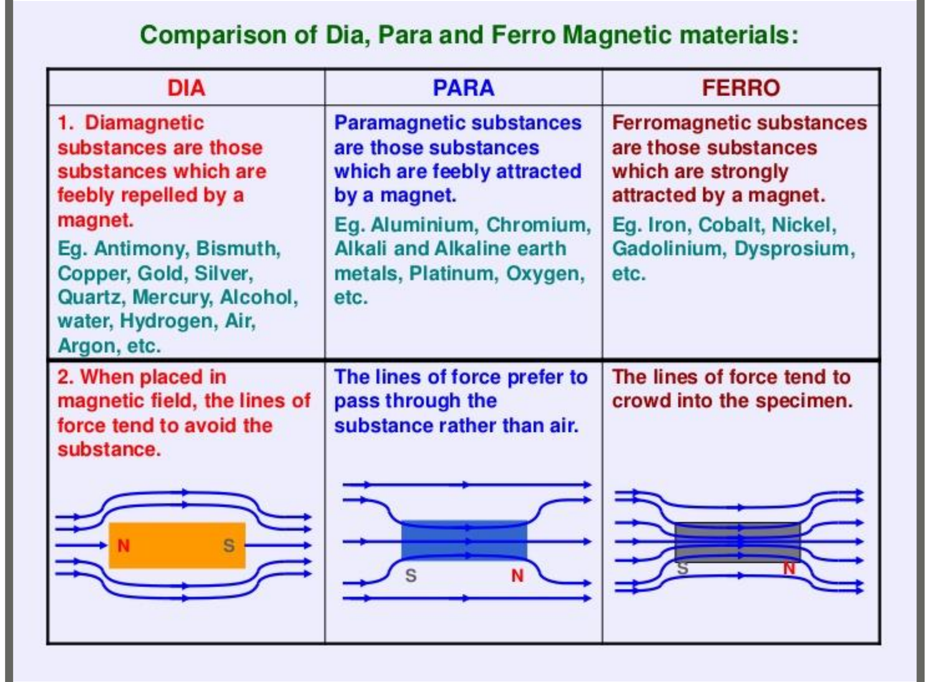


Dielectric permittivity

$$\epsilon = \epsilon_0 \epsilon_r$$

$$\epsilon_r = 1 + \chi_e$$

relative permittivity



Comparison of Dia, Para and Ferro Magnetic materials:

DIA	PARA	FERRO
1. Diamagnetic substances are those substances which are feebly repelled by a magnet. Eg. Antimony, Bismuth, Copper, Gold, Silver, Quartz, Mercury, Alcohol, water, Hydrogen, Air, Argon, etc.	Paramagnetic substances are those substances which are feebly attracted by a magnet. Eg. Aluminium, Chromium, Alkali and Alkaline earth metals, Platinum, Oxygen, etc.	Ferromagnetic substances are those substances which are strongly attracted by a magnet. Eg. Iron, Cobalt, Nickel, Gadolinium, Dysprosium, etc.
2. When placed in magnetic field, the lines of force tend to avoid the substance.	The lines of force prefer to pass through the substance rather than air.	The lines of force tend to crowd into the specimen.

$\mu_r < 1$ $\mu_r > 1$ $\mu_r \gg 1$

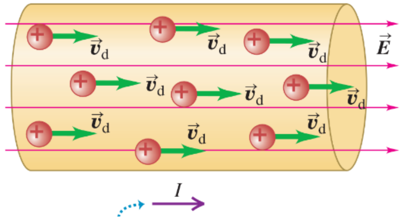
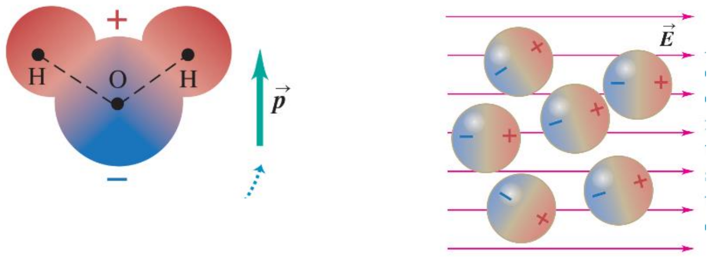
Magnetic permeability

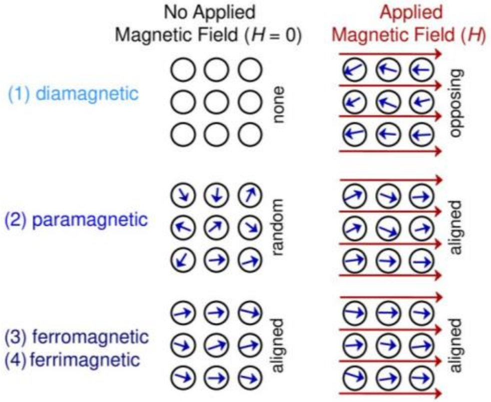
$$\mu = \mu_0 \mu_r$$

$$\mu_r = 1 + \chi_m$$

relative permeability

EM - material interaction: ***What properties can we get?***

Material Properties	Constitutive Relations	Diagrams
- **Electrical conductivity** (or resistivity), σ – *Measures the ability of a material to conduct electric current (conduction current)*	$$\mathbf{J} = \boxed{\sigma}\mathbf{E}$$	
- **Dieletric permittivity,** ϵ – *Some molecules have overall electric dipole moment (e.g. H_2O), which will align with an applied electric field and generate displacement (**D**) current.*	$$\mathbf{D} = \epsilon\mathbf{E}$$ $\epsilon = \epsilon_0\epsilon_r$	

- **Magnetic permeability,** μ
  – *Magnetic dipoles in the material interact with an applied magnetic field to give characteristic magnetic flux density.*
  – *Magnetic behaviors: diamagnetism, paramagnetism, ferromagnetism*
	$$\mathbf{B} = \boxed{\mu}\mathbf{H}$$
	$\mu = \mu_0\mu_r$
		
		
		$\mu_r < 1$
		$\mu_r > 1$
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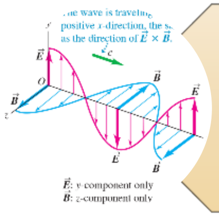

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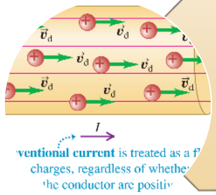

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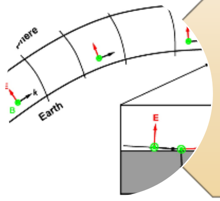

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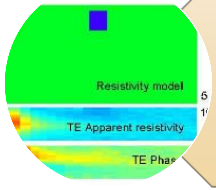

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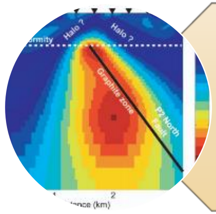


MT Analysis: Subsurface imaging and inferences

EM methods and their applications

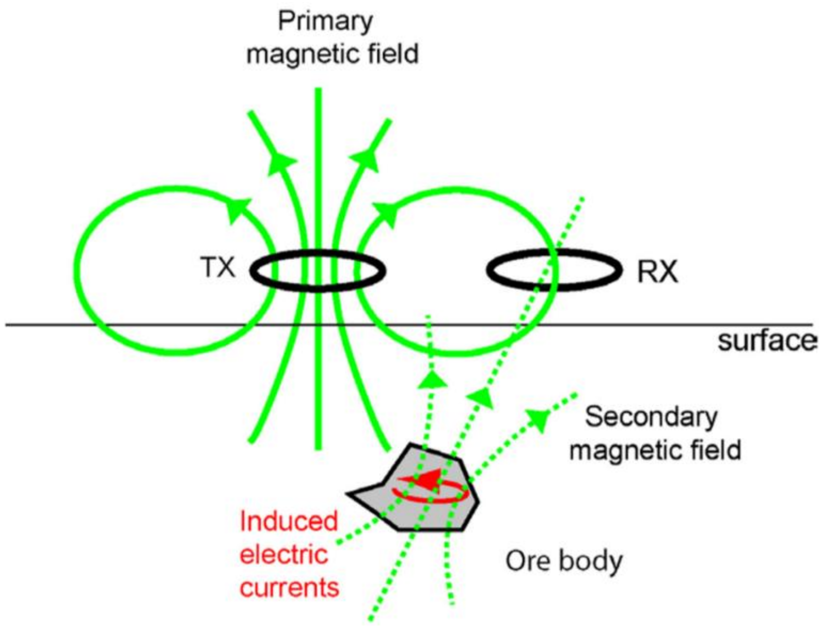
- ☒ Magnetotellurics (MT) – *natural source (plane wave), sinusoidal EM time variation*
- ☐ Loop-loop system, frequency domain systems – *dipolar B field source through transmitter, sinusoidal EM time variation*
- ☐ Time domain EM (TDEM) – *dipolar source, square wave EM variation (Fourier transform)*
- ☐ Ground-penetrating radar(GPR) – *high frequencies propagate as wave in the Earth, seismology techniques can be applied*

- Hydrogeology, mapping aquifers and contaminants
- Mineral exploration (e.g., graphite)
- Hydrocarbon exploration
- Geothermal exploration
- Tectonic and lithospheric studies
- Inferring mantle parameters (i.e., water content, melt, temperature)

Common features of all EM methods

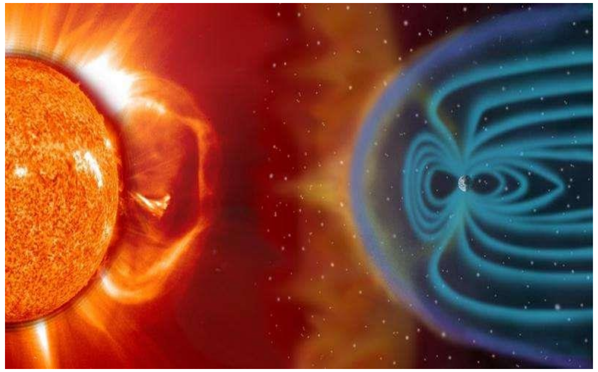
- **Primary EM field**
  - *incident on Earth*
  - *Can be man-made (dipole transmitter – active EM methods) or natural (plane wave – passive EM methods)*
- **Secondary EM field**
  - *Generated in the Earth by primary EM field*
  - *Eddy currents are induced, amplitude and phase of the signal is changed*
- **Ground response to the propagation of the EM fields (alternating E and B)**
- **Determine <u>electrical resistivity</u> profile**

Controlled source

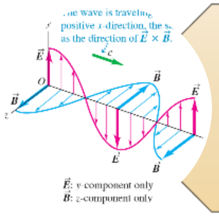


Natural sources

high frequency



low frequency



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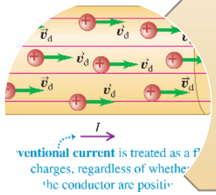

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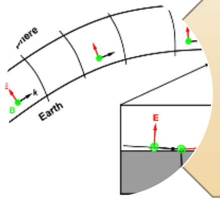

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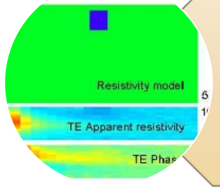

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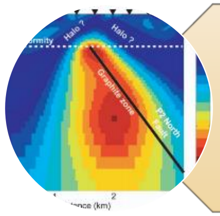


MT Analysis: Subsurface imaging and inferences

Maxwell's equations in action!

Ampere's law

$$\nabla \times \mathbf{B} = \mu\left(\mathbf{J} + \epsilon\frac{d\mathbf{E}}{dt}\right) \quad \text{OR} \quad \nabla \times \mathbf{H} = \underbrace{\mathbf{J}}_{\text{Conduction current}} + \underbrace{\frac{d\mathbf{D}}{dt}}_{\text{displacement current}}$$

Faraday's law

$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt}$$

These equations are coupled -- *can show that EM waves can travel in the Earth!*

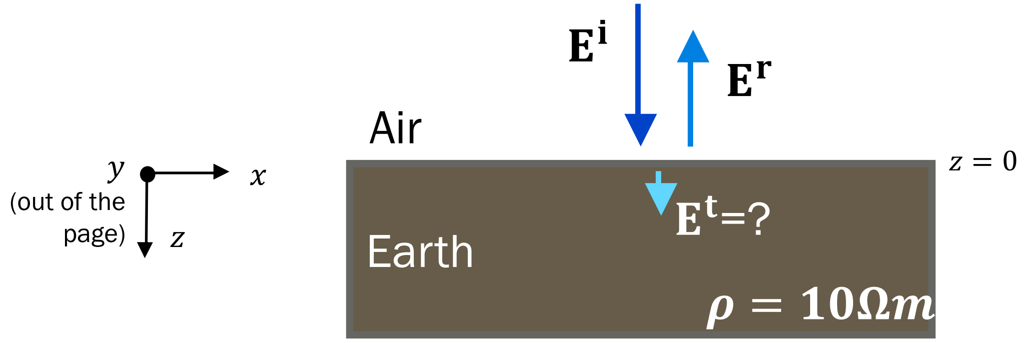
where:

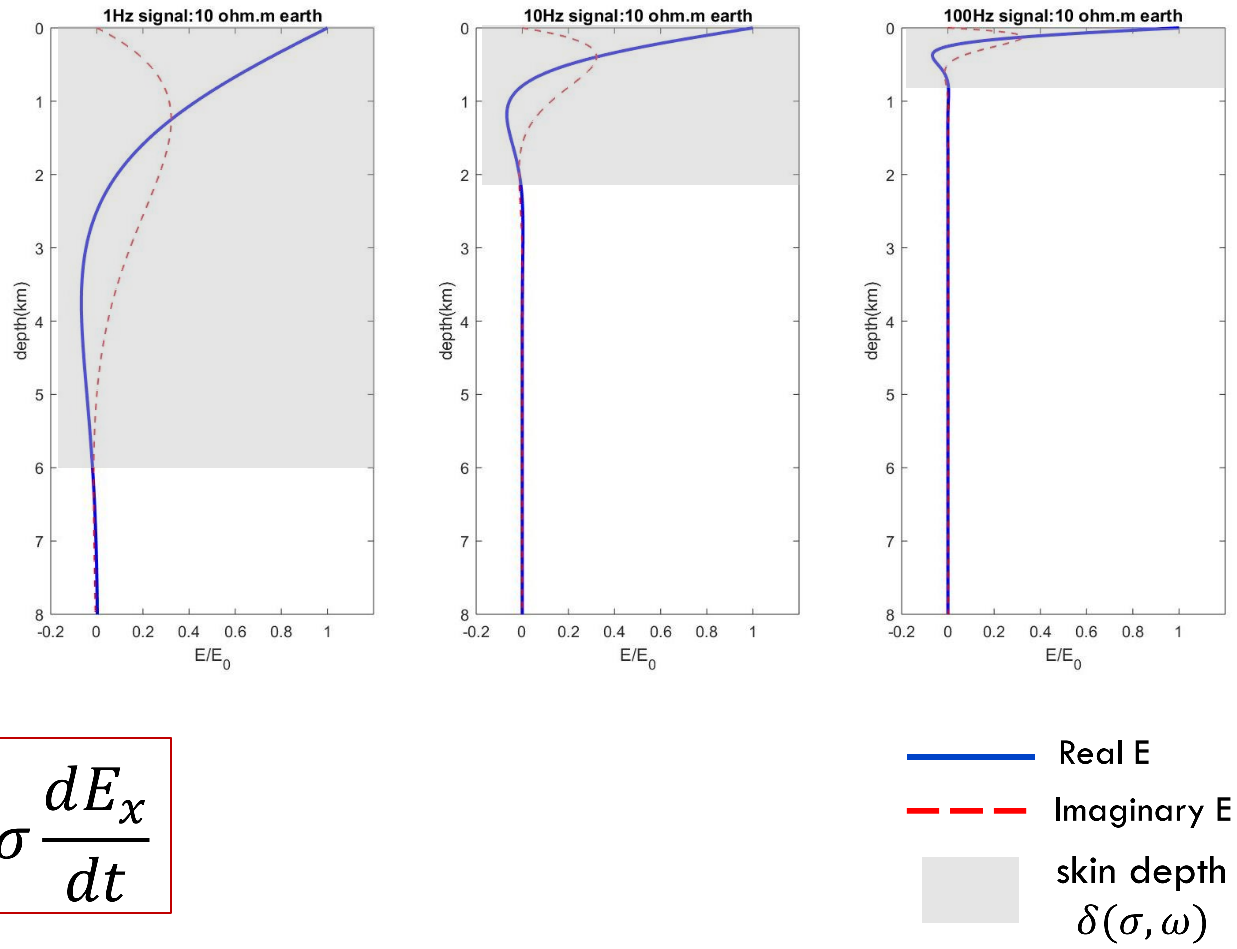
$$\mathbf{B} = \mu\mathbf{H}$$
$$\mathbf{D} = \epsilon\mathbf{E}$$
$$\mathbf{J} = \sigma\mathbf{E}$$

Faraday-Amperes law coupling:

Diffusion equation!

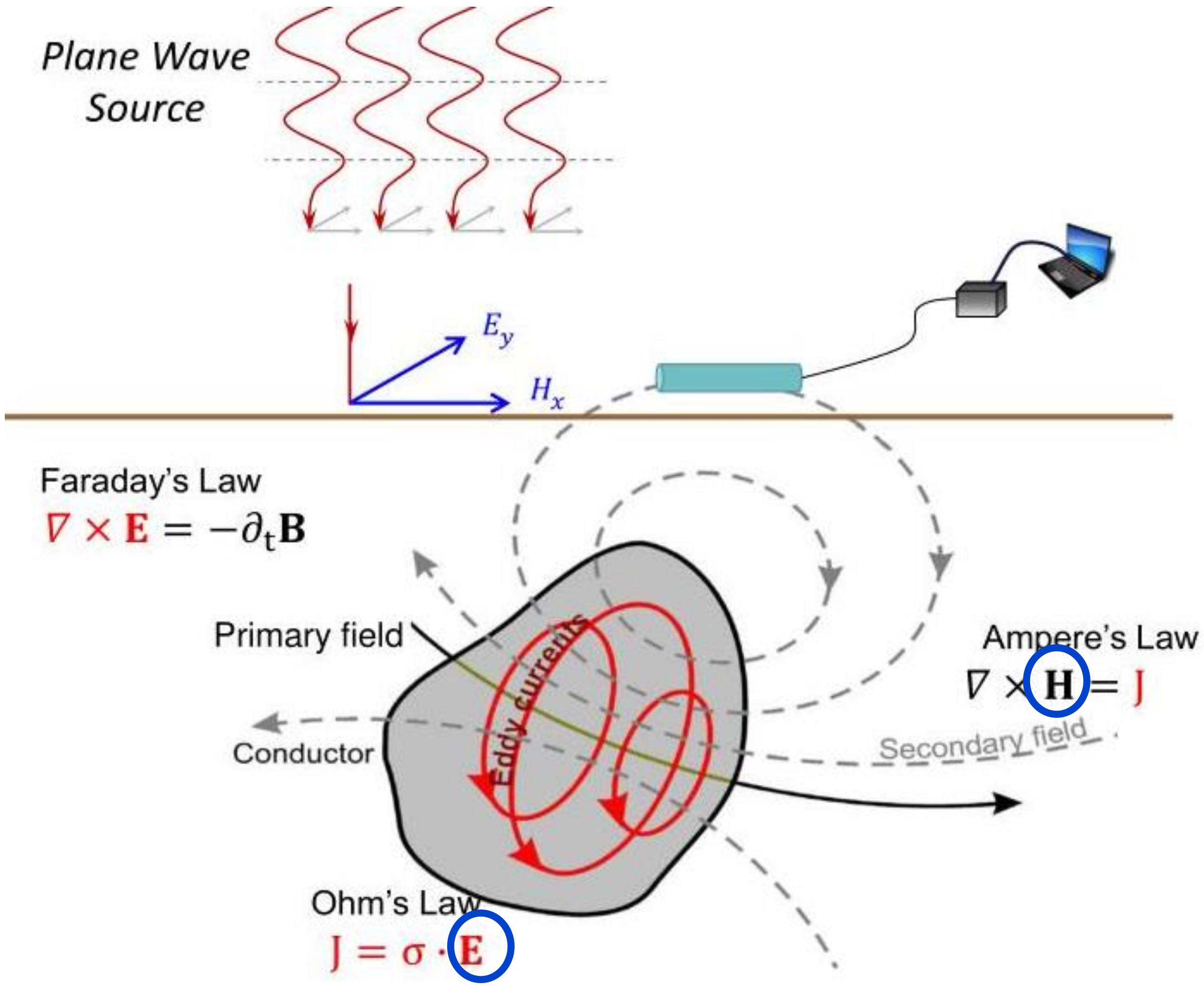
$$\nabla \times (\nabla \times \mathbf{E}) = -\left(\mu\sigma\frac{d\mathbf{E}}{dt} + \mu\epsilon\frac{d^2\mathbf{E}}{dt^2}\right) \Rightarrow \boxed{\frac{d^2E_x}{dz^2} = \mu\sigma\frac{dE_x}{dt}}$$



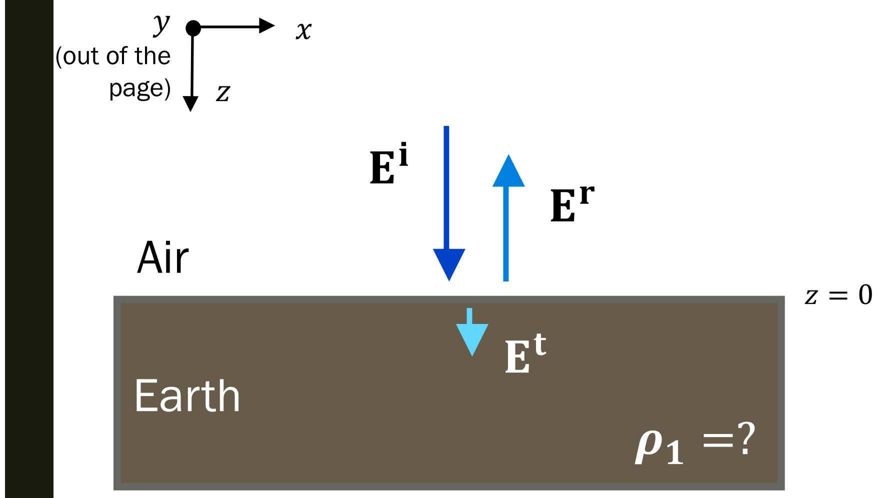


Maxwell’s equations in action!

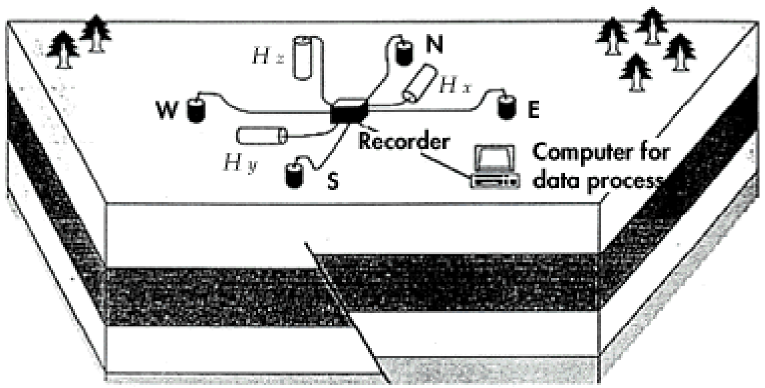
Electromagnetic Induction



What can we infer from MT?



surface measurements



From surface measurements, we can infer:

IMPEDANCE

$$\boxed{Z_{xy}(\omega) = \frac{E_x(\omega)}{H_y(\omega)} = \frac{(1-i)}{\sqrt{2}}\sqrt{\frac{\omega\mu_0}{\sigma_1}}}$$

RESISTIVITY

$$\rho_1 = \frac{1}{\sigma_1} = \frac{1}{\omega\mu_0}\left|Z_{xy}\right|^2 = \frac{1}{\omega\mu_0}\left|\frac{E_x}{H_y}\right|^2$$

But, resistivity is NOT CONSTANT in Earth!
Thus, consider:

APPARENT RESISTIVITY

$$\rho_a(\omega) = \frac{1}{\omega\mu_0}\left|\frac{E_x(\omega)}{H_y(\omega)}\right|^2$$

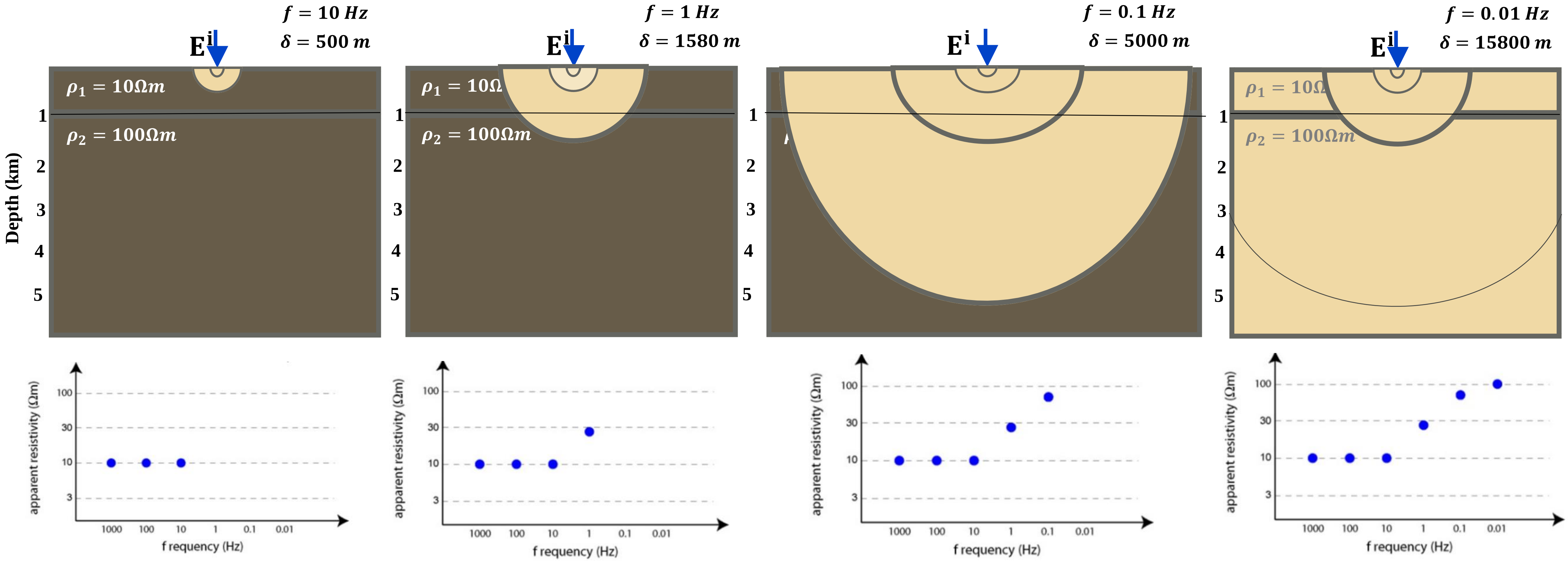
(average over a hemisphere with radius = δ)

PHASE ANGLE

$$\Phi(\omega) = \tan^{-1}\left[\frac{E_x(\omega)}{H_y(\omega)}\right]$$

$\frac{\pi}{4}$ in halfspace

Apparent resistivity from MT



APPARENT RESISTIVITY $\rho_a(\omega) = \frac{1}{\omega\mu_0}\left|\frac{E_x(\omega)}{H_y(\omega)}\right|^2 = \frac{1}{\omega\mu_0}\left|Z_{xy}(\omega)\right|^2$

SKIN DEPTH $\delta = \sqrt{\frac{2}{\omega\mu\sigma}} = \frac{503}{\sqrt{\sigma f}} = 503\sqrt{\rho T}$

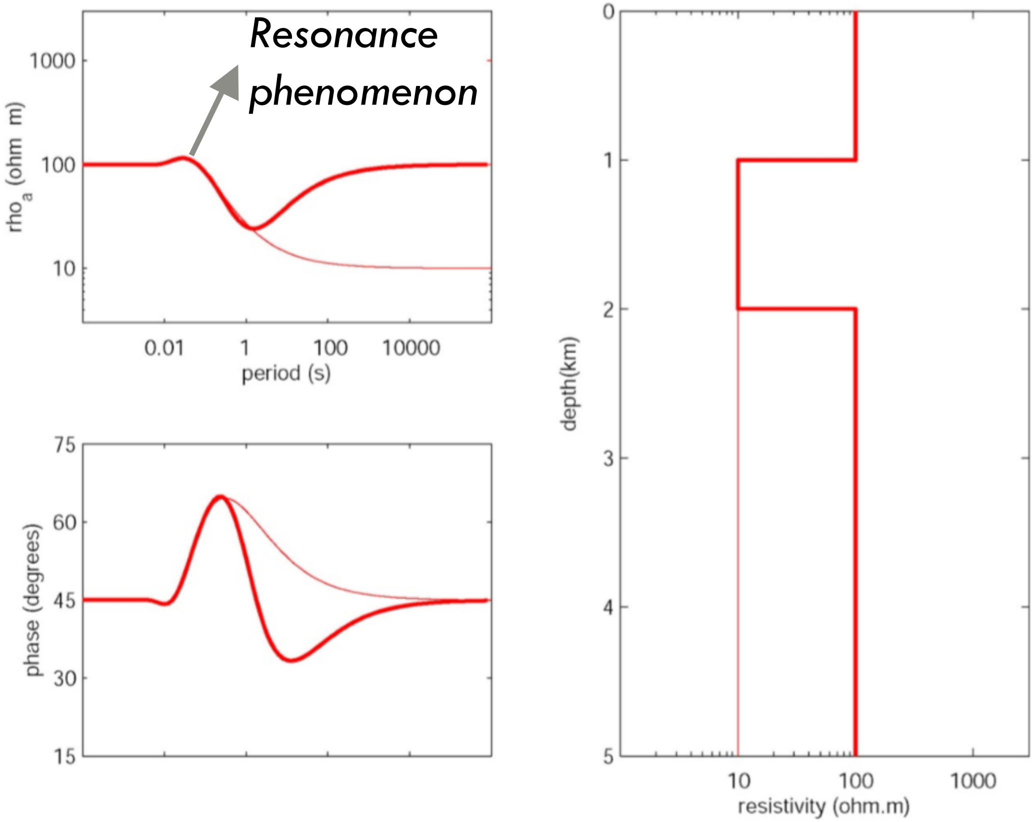
Sensitivity of MT to subsurface resistivity variations

APPARENT RESISTIVITY $\rho_a(\omega) = \frac{1}{\omega\mu_0}\left|Z_{xy}(\omega)\right|^2$

PHASE ANGLE $\Phi(\omega) = \tan^{-1}\left[\frac{E_x(\omega)}{H_y(\omega)}\right]$

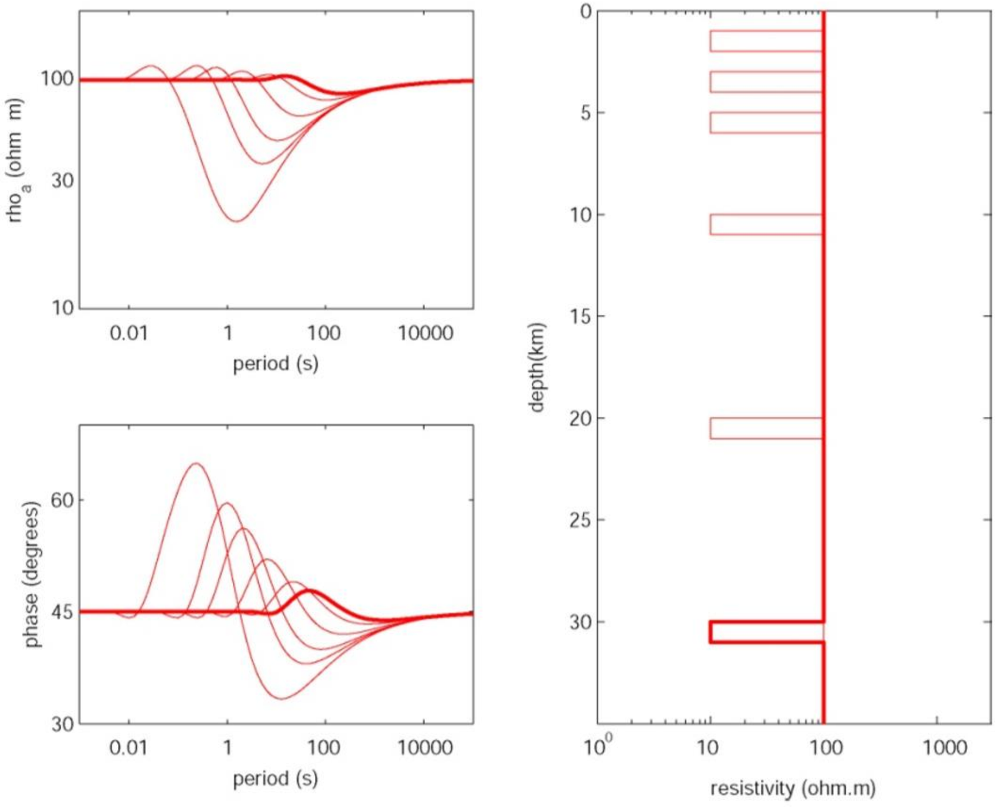
— 2 layer model

— 3 layer model



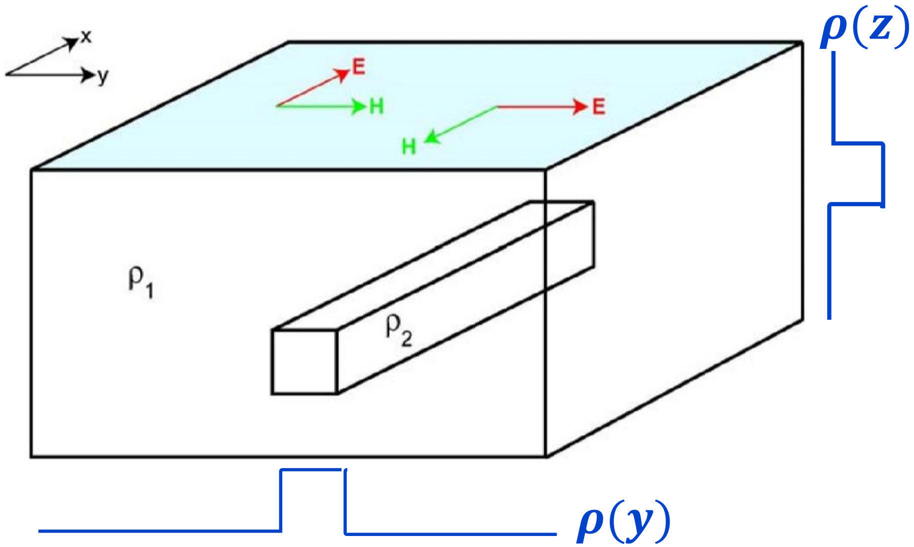
ρ_a **increases** with depth: $\Phi < \frac{\pi}{4}$

ρ_a **decreases** with depth: $\Phi > \frac{\pi}{4}$

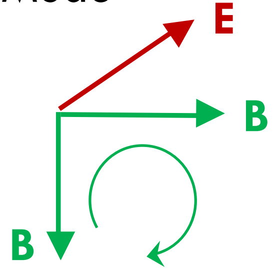


magnitude of response **decreases** as the layer becomes **deeper**

2D Earth resistivity model: an inverse problem

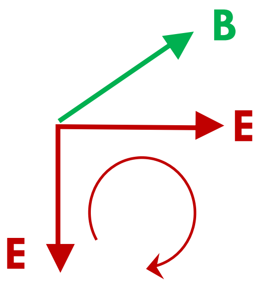


Transverse Electric (TE) Mode



Induced electric field

Transverse Magnetic (TM) Mode



Induced magnetic field

MT Data *Resistivity Mode*

$$\mathbf{d} = \mathbf{F}\,[\mathbf{m}]$$

[NON-UNIQUE SOLUTION]

- Inherent non-uniqueness
  (integration of thickness and conductance)

Surface measurements *Surface measurements*

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \underline{\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{zz} \end{pmatrix}} \begin{pmatrix} H_x \\ H_y \end{pmatrix}$$

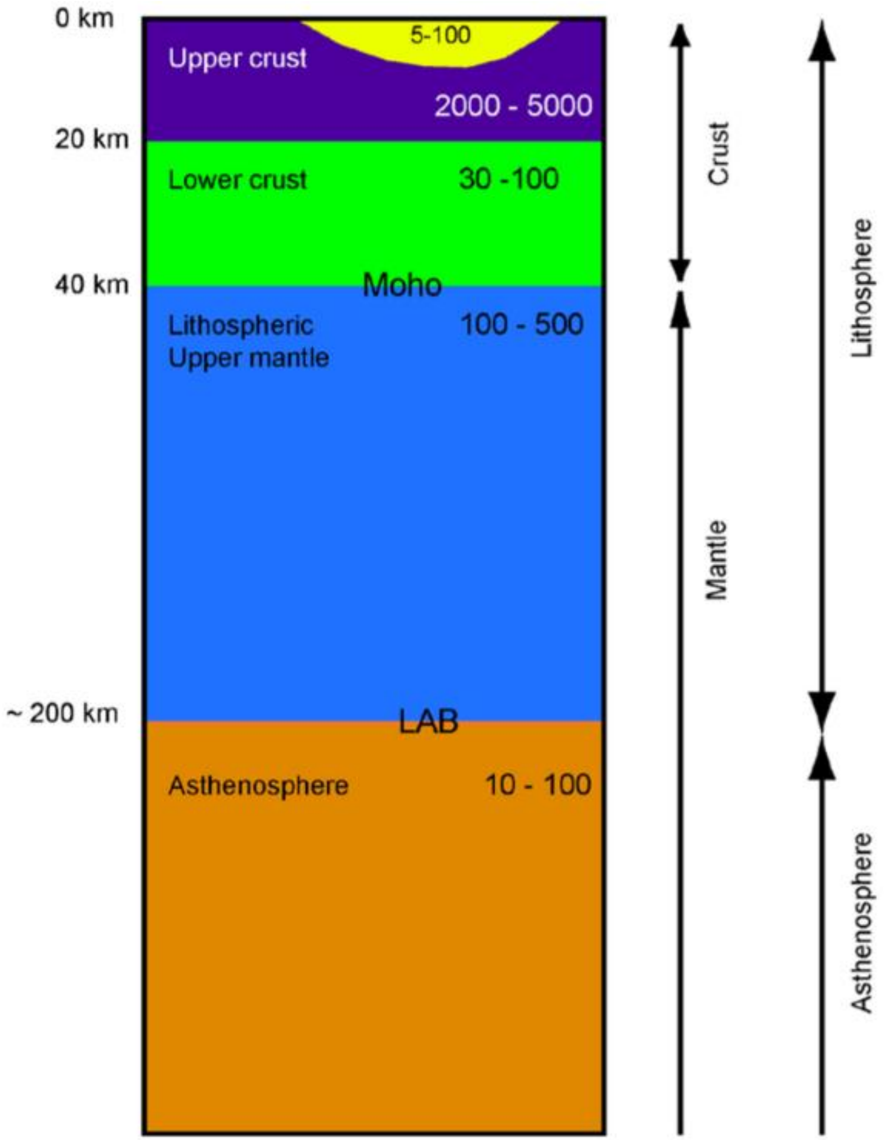
Impendance tensor - calculated

$\rho_a(\omega)$ *and* $\Phi\,(\omega)$

OCCAM INVERSION algorithm
(deGroot-Hedlin and Constable, 1990)

Electrical resistivity model

Inferred subsurface electrical resistivities



What are these resistivities telling us about the Earth structure?

need
experimental data
for these rocks!

Factors affecting ***electrical resistivity***

OHM's LAW:

Current density *Electric field*

$$\mathbf{J} = \sigma\, \mathbf{E}$$

Electrical conductivity (material property)

Electrical resistivity

$$\rho = \frac{1}{\sigma} = \frac{E}{J} = \frac{1}{nq\mu_{\text{mob}}}$$

- *idealized model*
- *resistivity ρ is constant*

where:

- *n number of charge carriers*
- *q is the charge*
- *μ_{mob} mobility of the charge carriers*

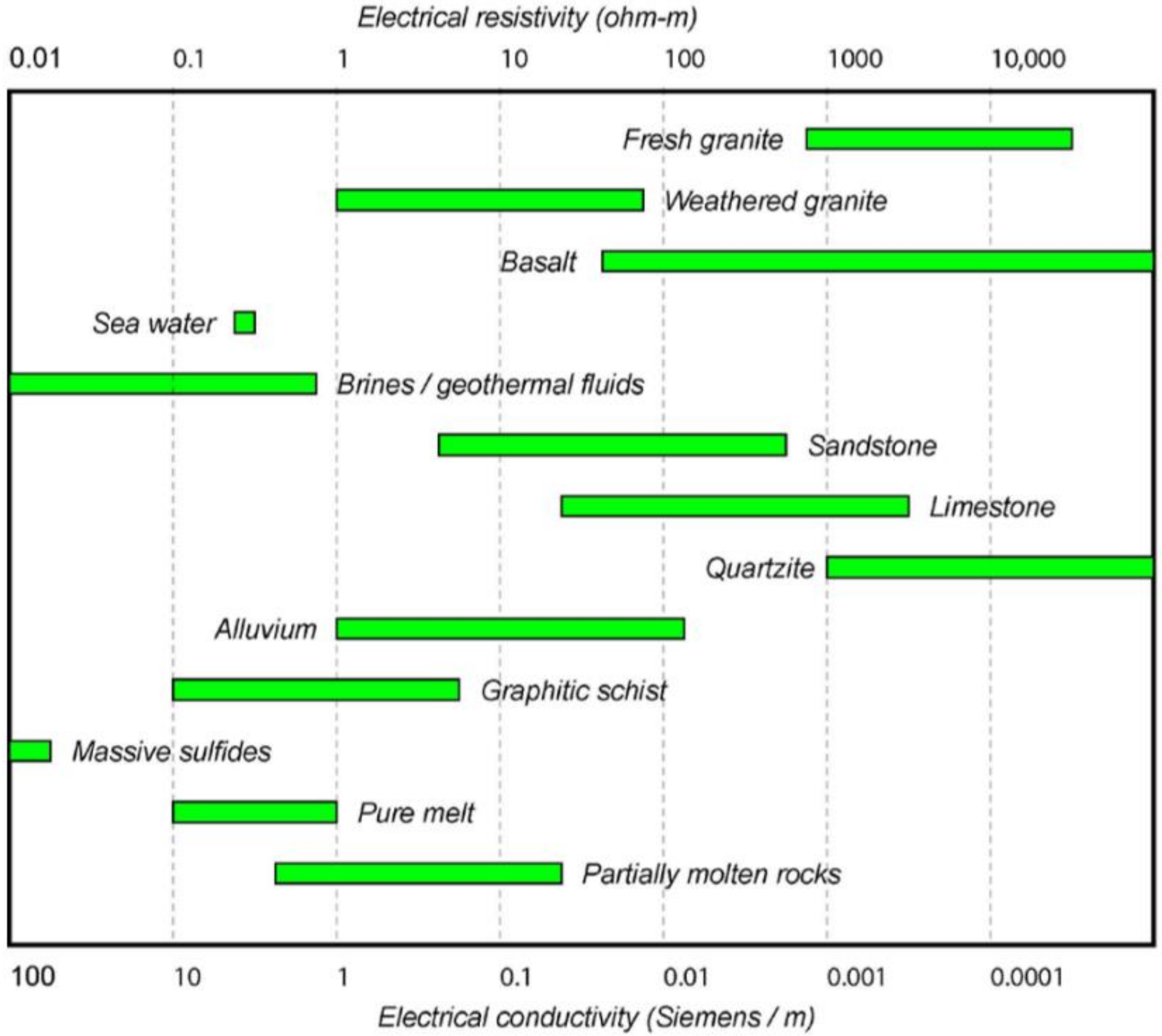
What about the Earth's materials?

- Non-ohmic or nonlinear behavior (i.e., semi conduction, $\rho \propto e^{\frac{E^*}{kT}}$)
- Electrical resistivity or conductivity is affected by (1) temperature and number of charge carriers like (2) presence of hydrogen ions

Empirically, conductivity (proton) is

$$\sigma = A_e \underset{(2)}{\underline{C_w^{r_e}}} \exp\left(-\frac{E_e^* + PV_e^*}{R\underset{(1)}{\underline{T}}}\right)$$

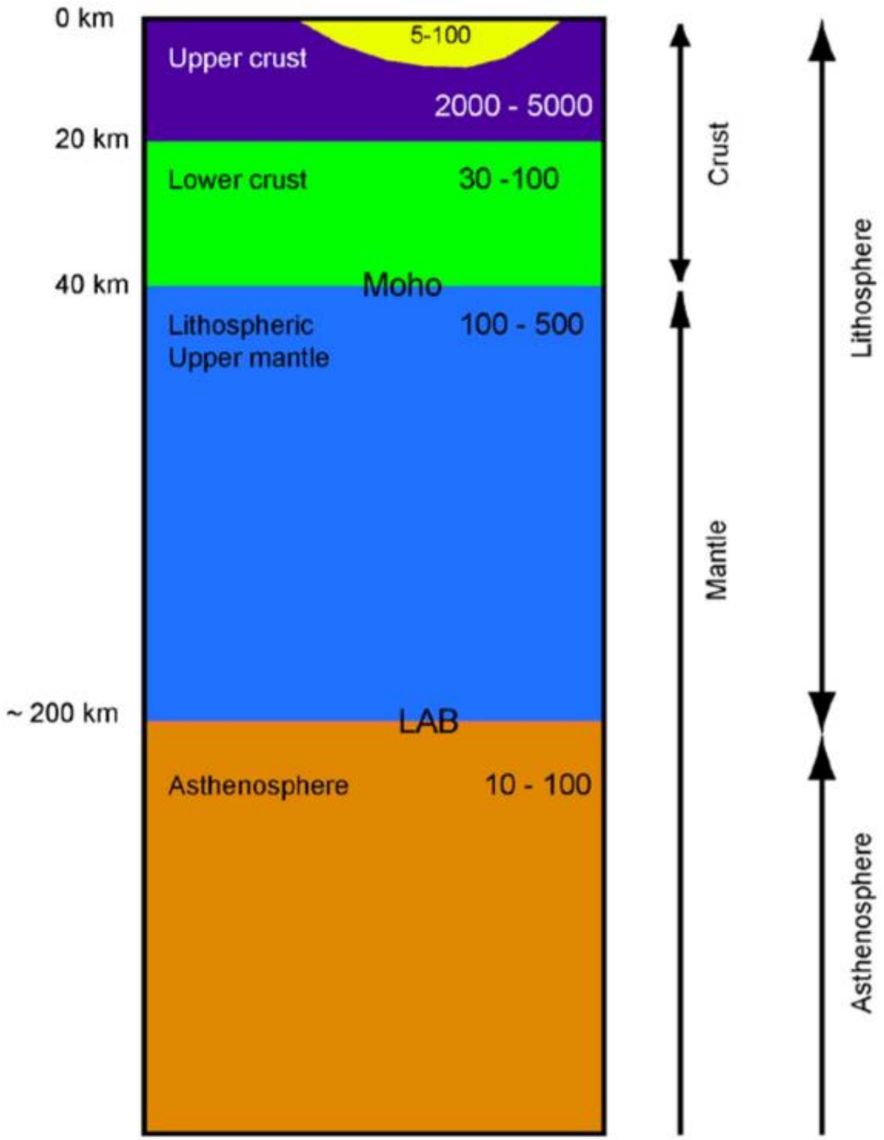
Electrical resistivities of common rocks



Other controlling factors that affect the charge carrier distribution and their mobility:

Factors	Increase ρ	Decrease ρ
Pore fluid	Reduce/ remove	Add more
Salinity of pore fluid	Decrease	Increase
Mineral deposition	Lithification (block pores)	Add clay minerals
interconnection between pores at constant fluid content	Decrease connection (spherical pores, high wetting angle)	Increase/ improve connection (elongated pores, low wetting angle)

Inferred subsurface electrical resistivities



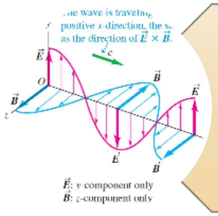
low resistivity due to sedimentary rocks with significant porosity and saline pore fluids

high resistivity due to low porosity crystalline rocks (igneous and metamorphic)

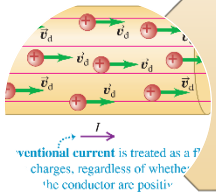
low resistivity could be due to fluids or graphite

intermediate resistivity

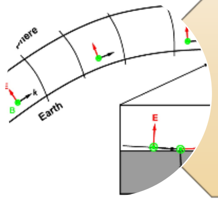
low resistivity, few percent partial melt



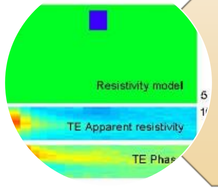
What is EM wave?



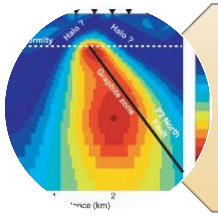
EM - matter interaction: What can we infer?



EM methods: overview



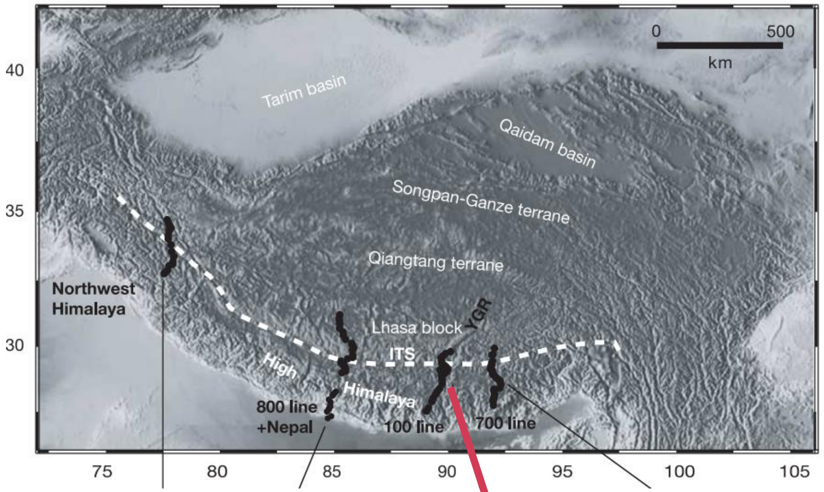
How MT measures and infers Earth’s property?



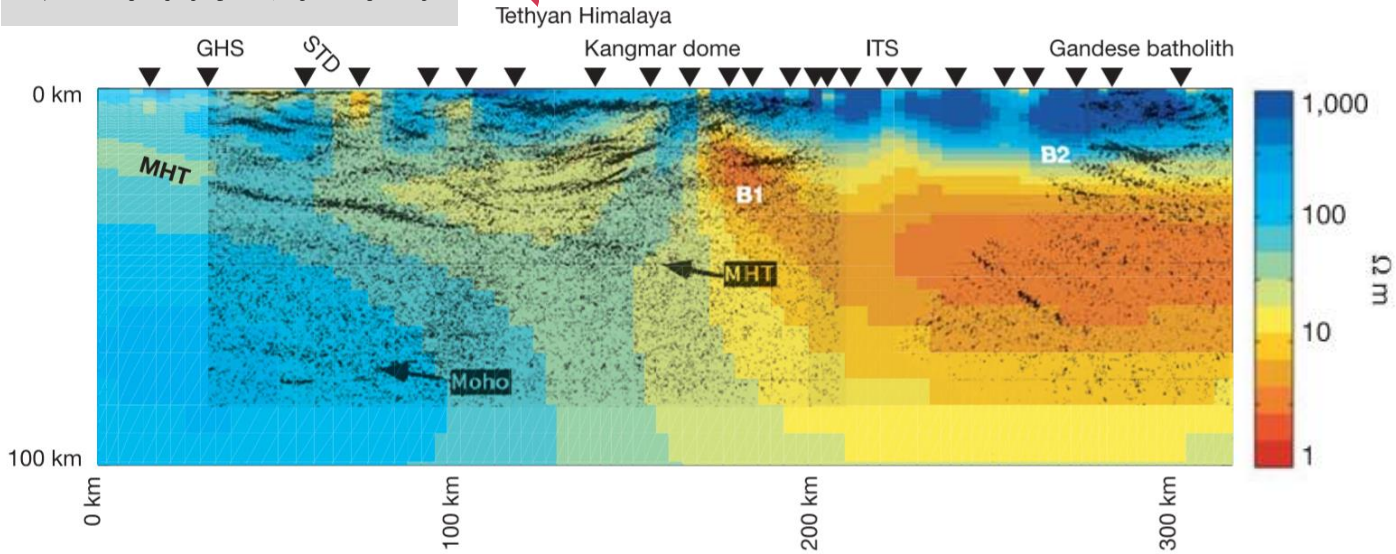
MT Analysis: Subsurface imaging and inferences

Crustal melting inferred from MT

Study area

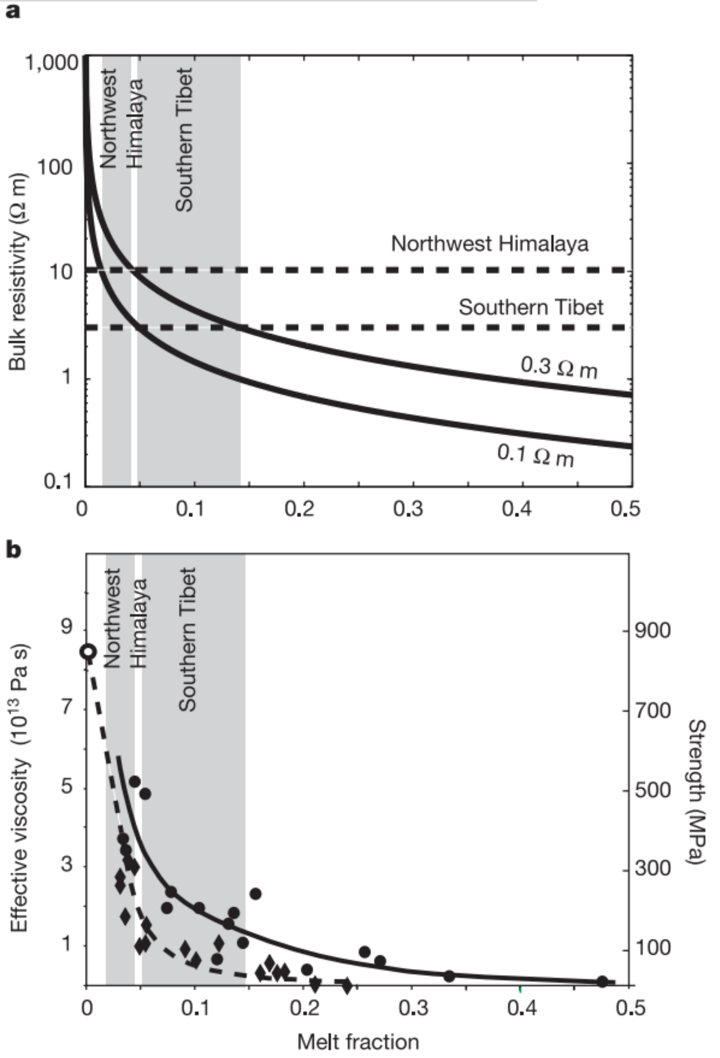


MT observations



Low resistivity region indicates presence of fluids (partial melt) – may be weak to flow over geological time

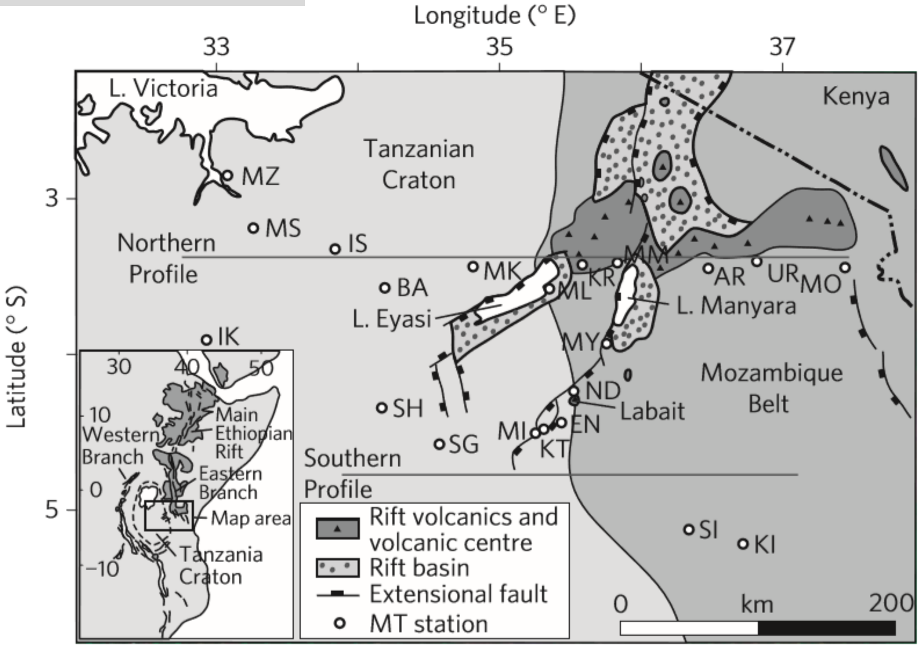
Inferred properties



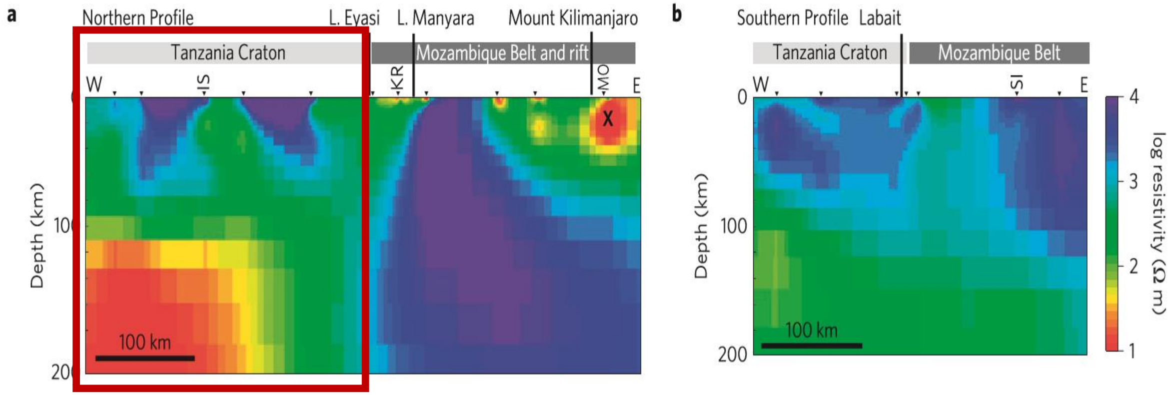
Unsworth, et al. (2005)

East African rift: weakening not by high hydrogen content?

Study area



MT observations

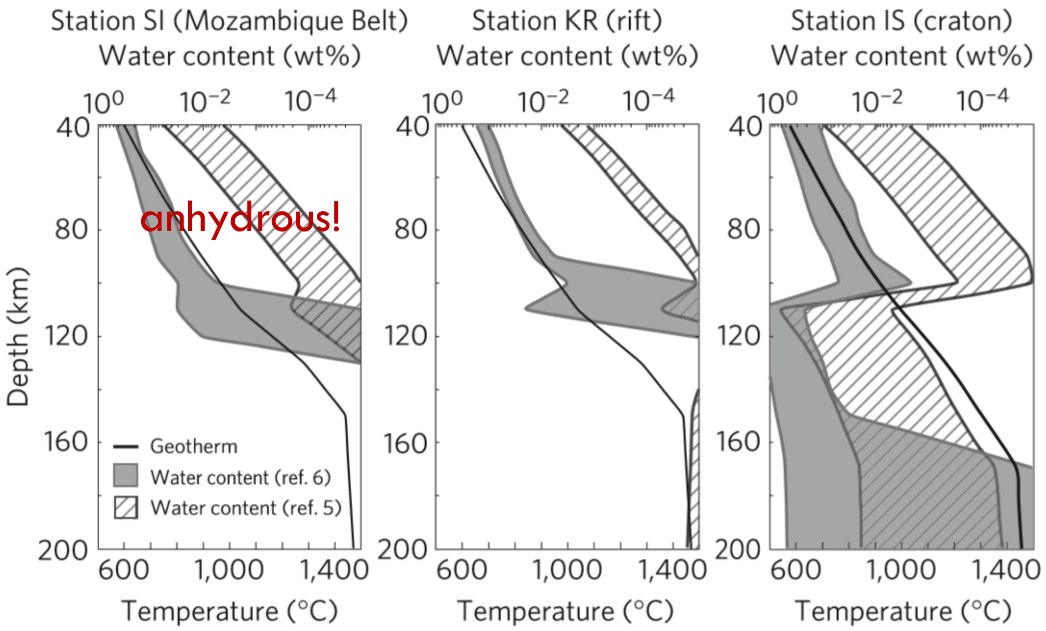


more conductive than Mozambique belt and rift??

Selway (2015)

Small grain size may control the localized rifting in East Africa

Inferred properties

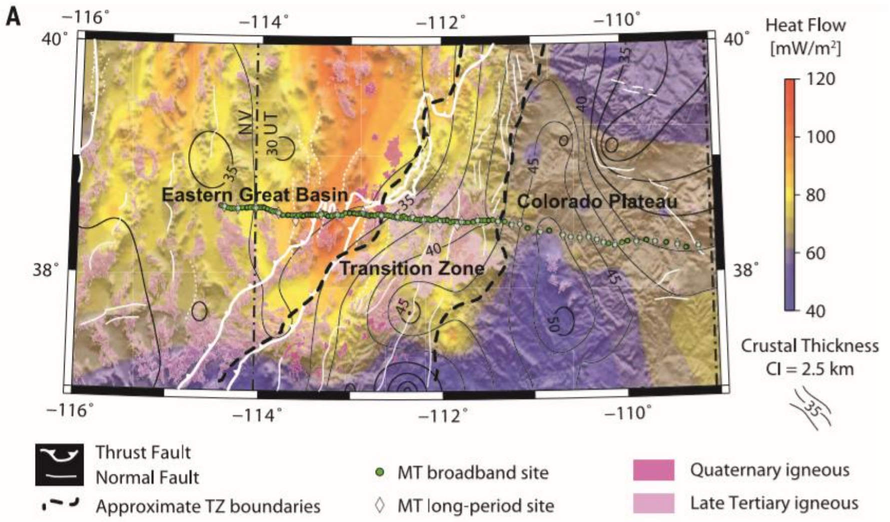


rich in hydrogen

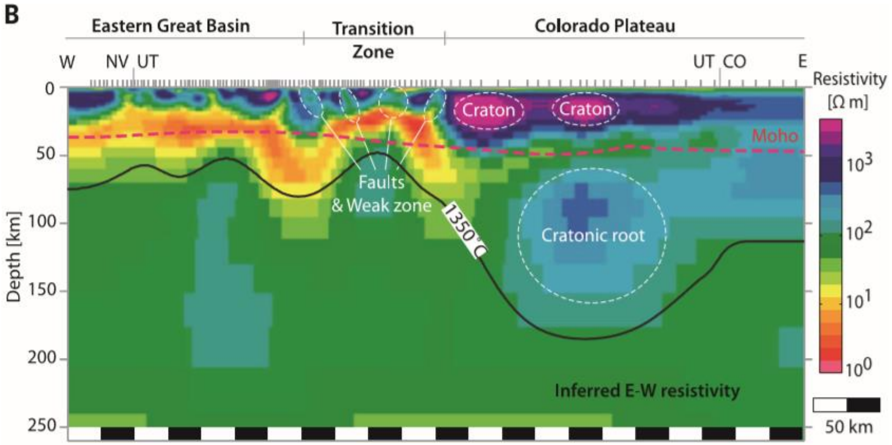
Inferred lithosphere viscosity structure from MT

MT-inferred viscosity predicts the topography, lithospheric deformation and mantle upwelling

Study area

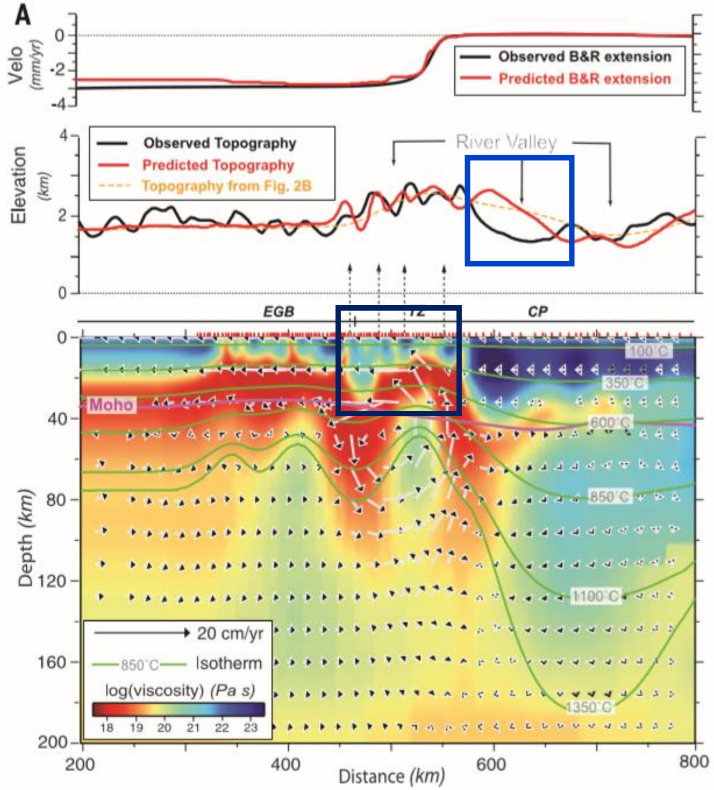


MT observations



Liu & Hasterok (2016)

Inferred properties



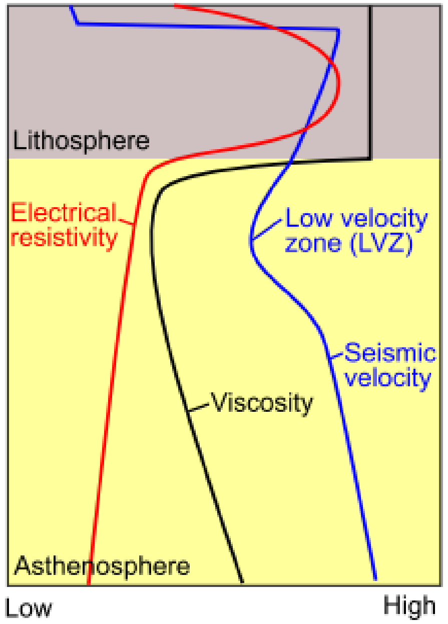
BUT…

- deformation within CP is overpredicted
- lack of localized crustal weak zones

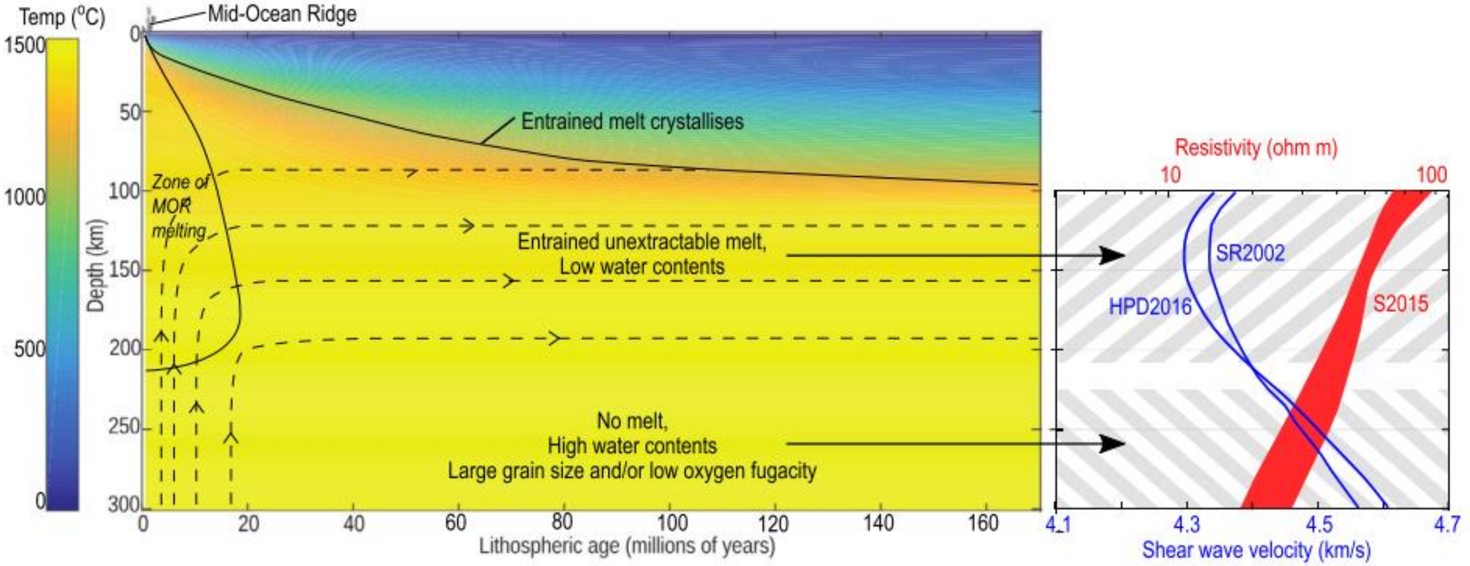
may be due to exclusion of compositional and grain size variations in viscosity calculation

LVZ due to melt? Or water?

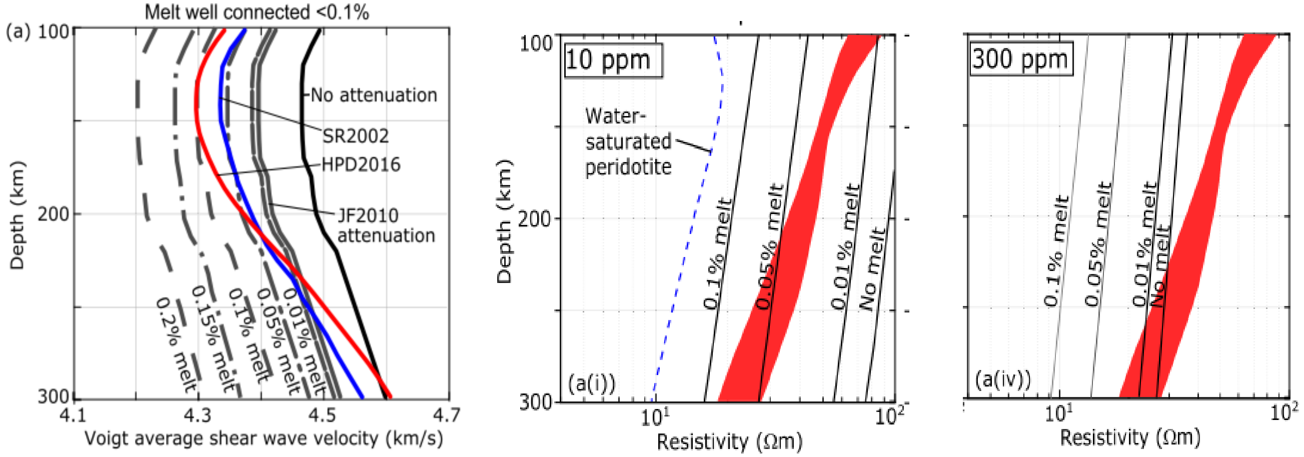
MT and seismic analysis



Inferences



Geophysical observations

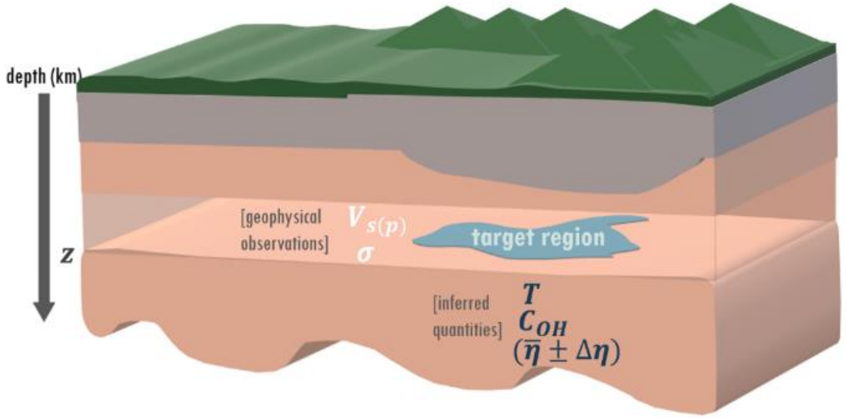


LVZ caused by a small amount of melt, not water

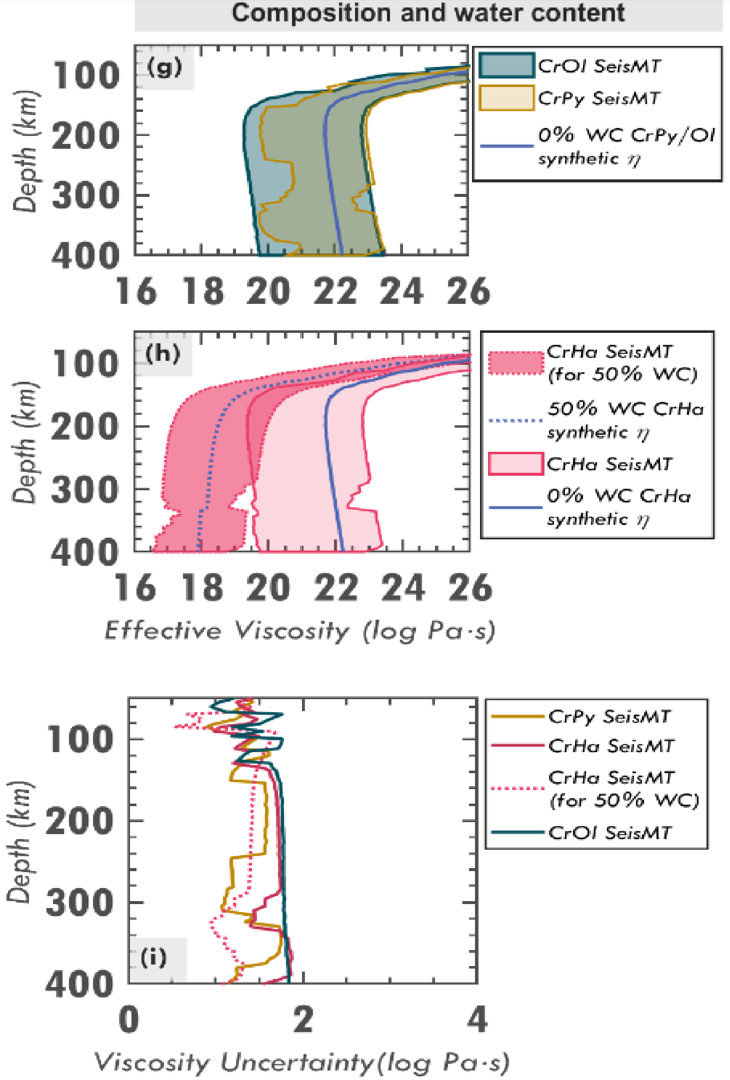
Selway & O'Donnell (2019)

Integrating MT, seismics and mineral physics to constrain viscosity structure

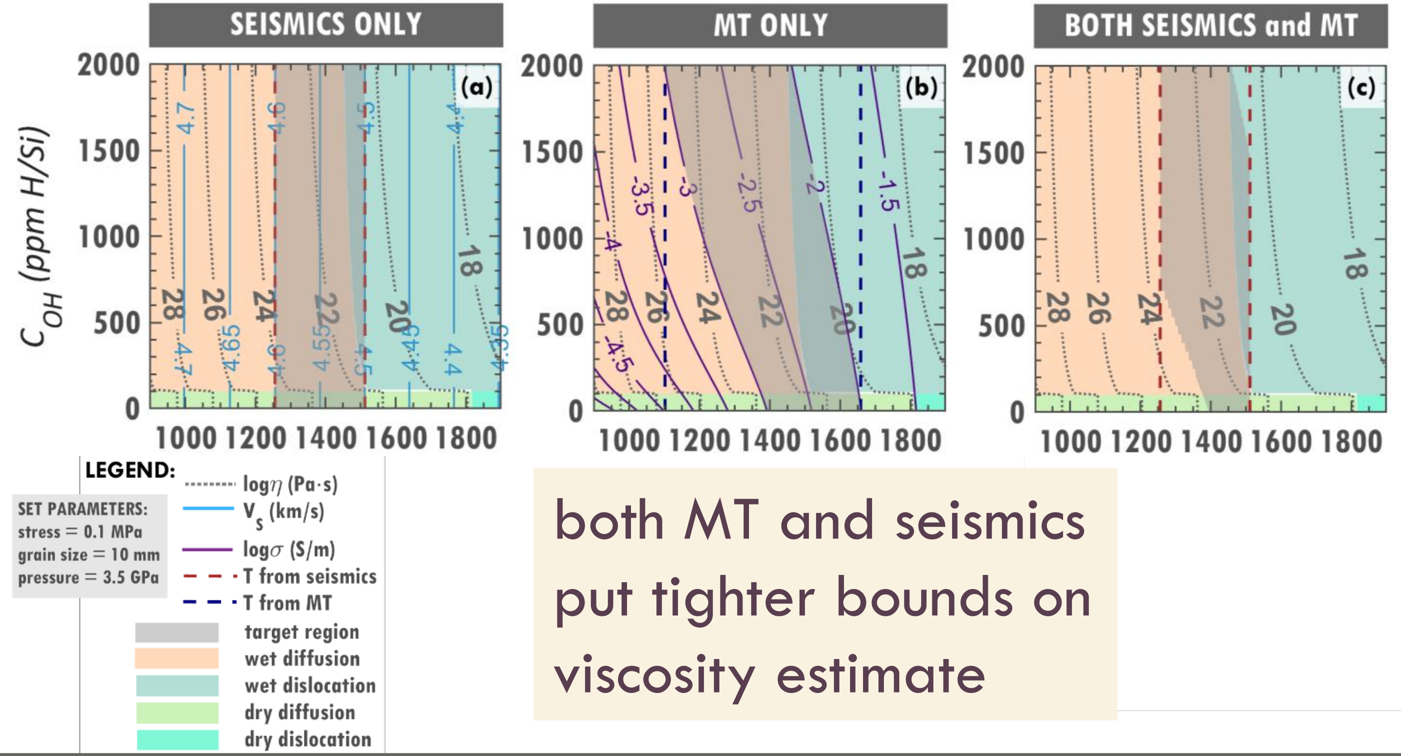
Set-up



account compositional variations when estimating viscosity



Results



both MT and seismics put tighter bounds on viscosity estimate

Ramirez, et al. (in prep)

Where are we now?

- Combined MT and seismic anaylsis in inferring subsurface structure
- Electrical anisotropic inversion has performed (e.g. Evans et al., 2005)
- Use of 3D MT inversion to determine thermochemical lithospheric structure of specific areas (limited Earth's surface coverage)
- 1D joint inversions (MT and seismic data) (e.g. Moorkamp et al., 2007)

Future works?

- Develop 3D joint inversion approaches (MT and seismic)
- Combining EM data with other geophysical data in doing analysis and interpreation, and exploit complementary sensitivities and uncertainties
- **Need to have a lot of MT data! --- need to do electrical conductivity experiments for other minerals!**

TUSEN TAKK!

QUESTIONS?

CEED
The Centre for Earth Evolution and Dynamics

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