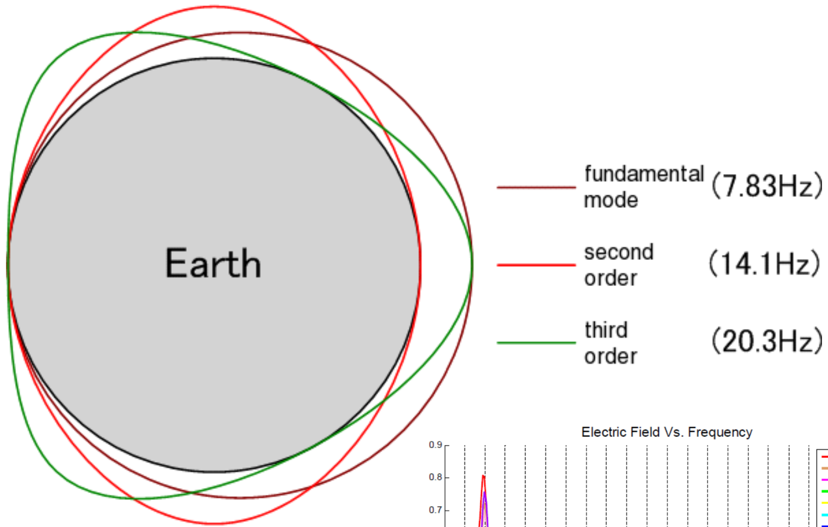
Magnetotelluric (MT) Method

Telluric currents: Currents in the Earth's crust and uppermost mantle. Telluric currents are **diurnal**, with a flow "towards the sun" - continuously move between the sunlit and shadowed sides of the earth: toward the equator on the side of the earth facing the sun, and toward the poles on the night side of the planet.

30+ physical mechanisms identified, but dominated (esp. at long wavelengths) by ***Geomagnetic Induction*** due to ionospheric and magnetospheric currents, themselves caused by interactions between the solar wind and the magnetosphere or solar radiation effects on the ionosphere.

The space between the surface of the Earth and the conductive ionosphere acts as a closed ***electromagnetic waveguide***. The limited dimensions of the Earth cause this waveguide to act as a resonant cavity for EM-waves in the Extremely Low Frequency band (***ν=3–60 Hz, λ=100,000–5000 km***). These resonances are named after Schumann, who predicted them in 1952. Since the cavity is naturally excited by electric currents in lightning, these resonances have been used to track global lightning activity.



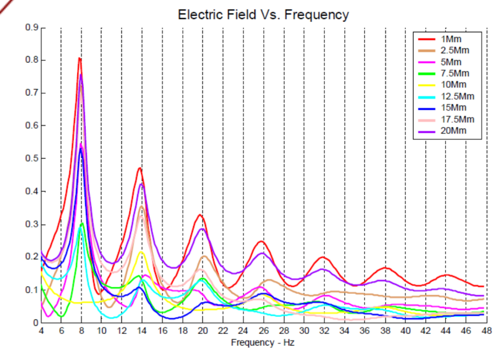


Figure 2. Electric field spectra as a function of SOD [40].

Wikipedia, and Price 2016

Magnetotelluric (MT) Method

Basic Idea:

Measure electric potential on the Earth's surface at different points, enabling the calculation of the magnitudes and directions of the telluric currents and hence the Earth's conductance/resistivity. Specifically, ***simultaneously*** measure the **B**– (≈ **H**, since crustal magnetic anomalies are small compared to the core-field) and **E–field** time-series in orthogonal directions at the Earth's surface.

Main goal:

MT theory allows the determination of the resistivity distribution in the subsurface, on depth scales ranging from a few tens of meters to hundreds of kilometers (Tikhonov, 1950; Cagniard, 1953), and is strongly dependent on the source frequency.

Passive method:

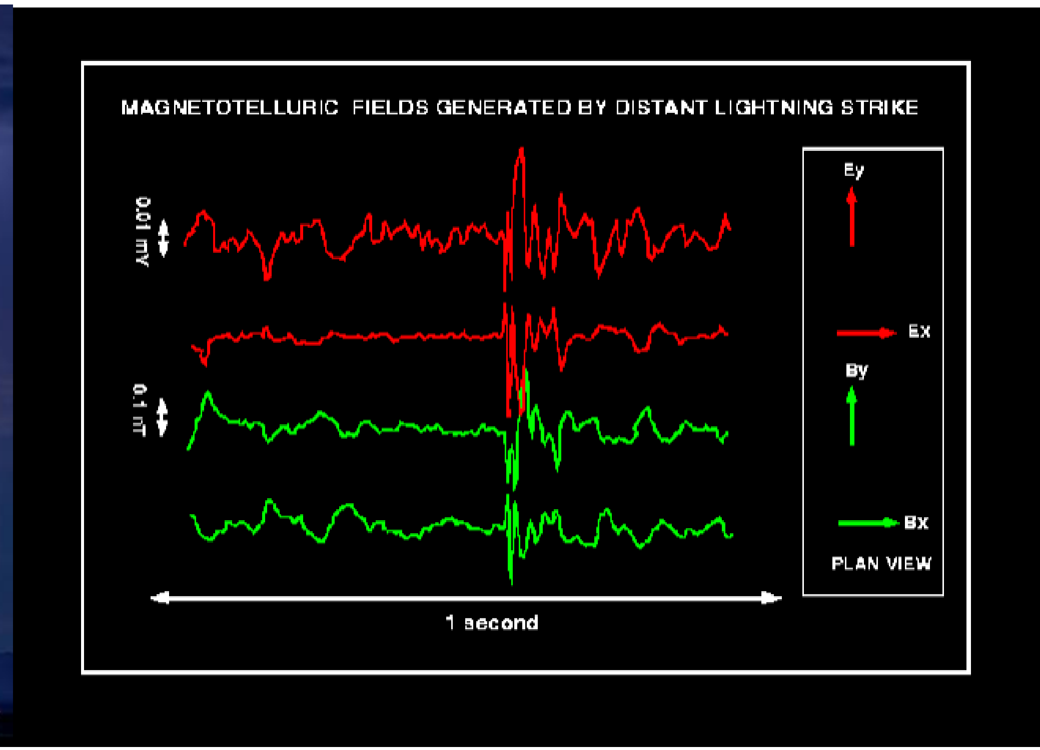
Uses natural geomagnetic energy variations as the power source

Magnetotelluric (MT) Method

Three highest-energy sources of electrical current in Earth:

(1) ***Global lightning strikes***
(1– 400 Hz, for example, for the U.S. Precision Lightning Network, or USPLN)

Gives ρ from 10s of m to a few km

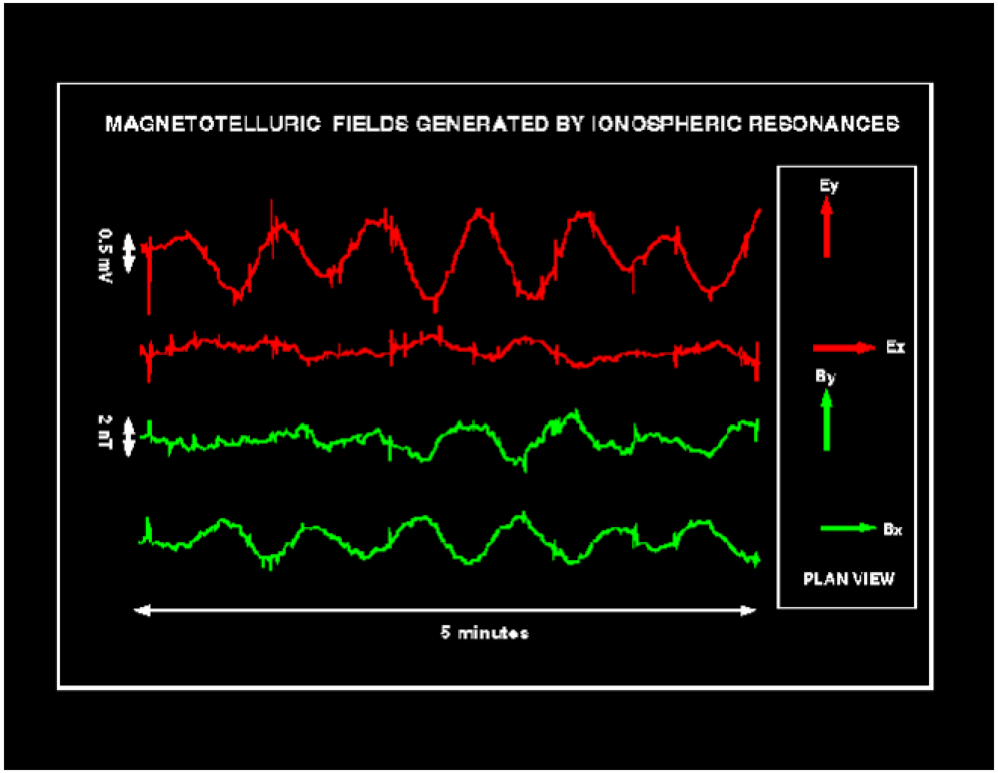


Magnetotelluric (MT) Method

Three highest-energy sources of electrical current in Earth:

(2) ***Ionospheric resonances***
(periods of seconds to minutes (***3-60 Hz***):
below, ~20 s period near Sunset)

Gives *ρ* from ~2 to 10 km



The small, high frequency spikes correspond to distant lightning strikes. Note that at the low frequencies at which MT is used, net magnetic field, ***H* ~ *B*.**

Magnetotelluric (MT) Method

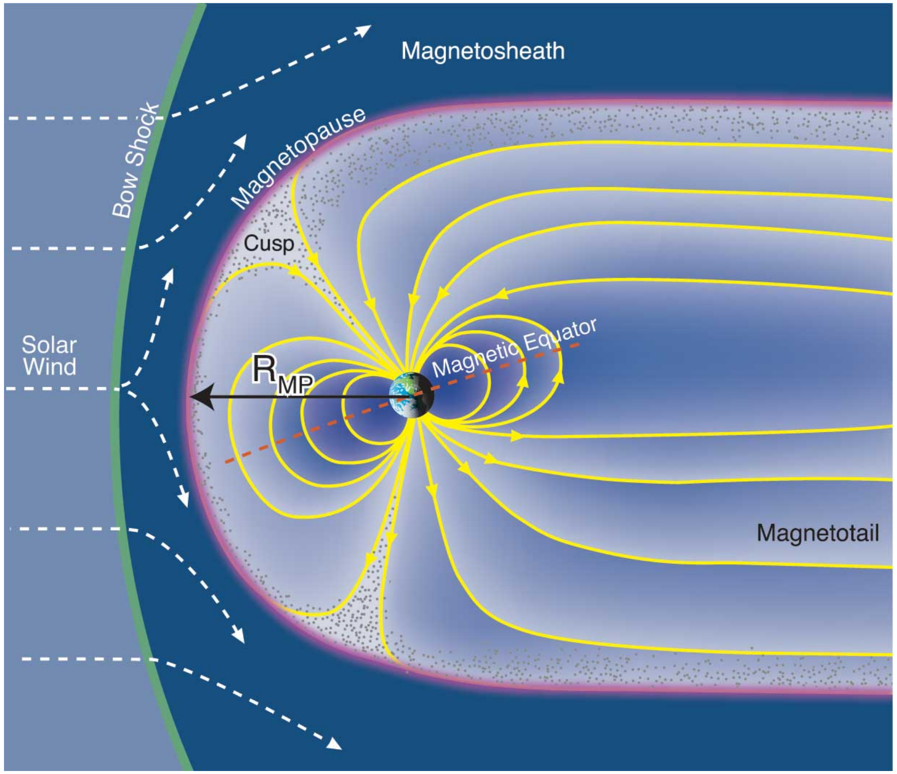
Three highest-energy sources of electrical current in Earth:

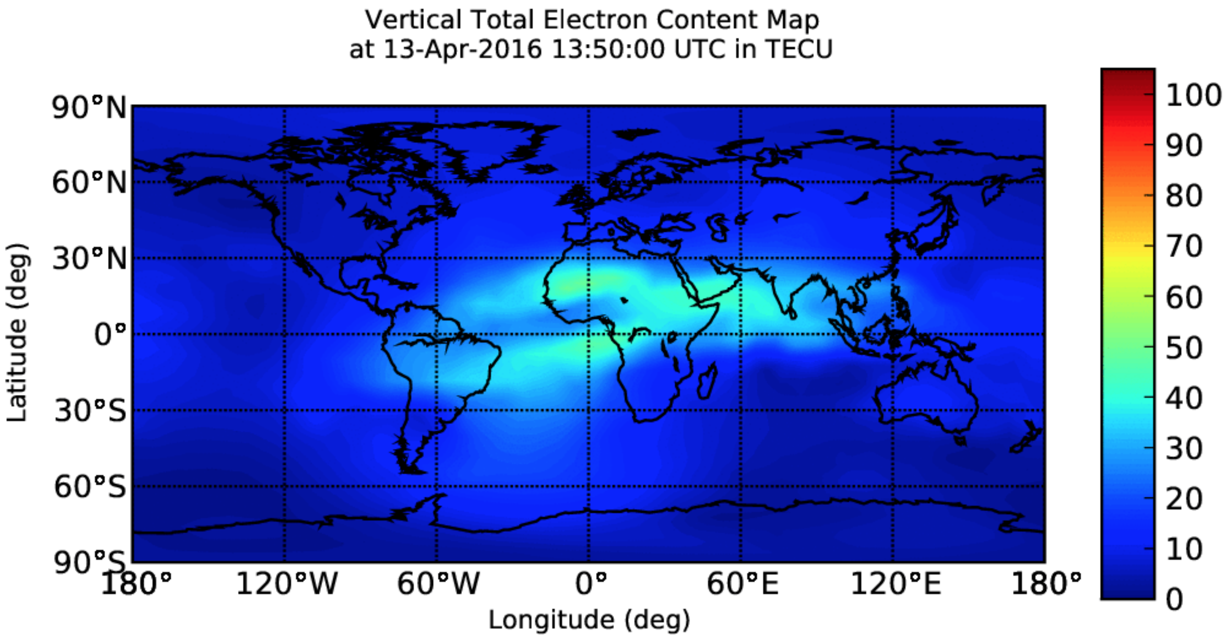
(3) ***Ionospheric disturbances:***

Caused by interactions of high energy particles and electrons emitted by the sun (periods of days and longer, or ***sub-1-Hz***)

Gives ρ from 10s to 100s of km

(& to the core if observed for long enough!!!)

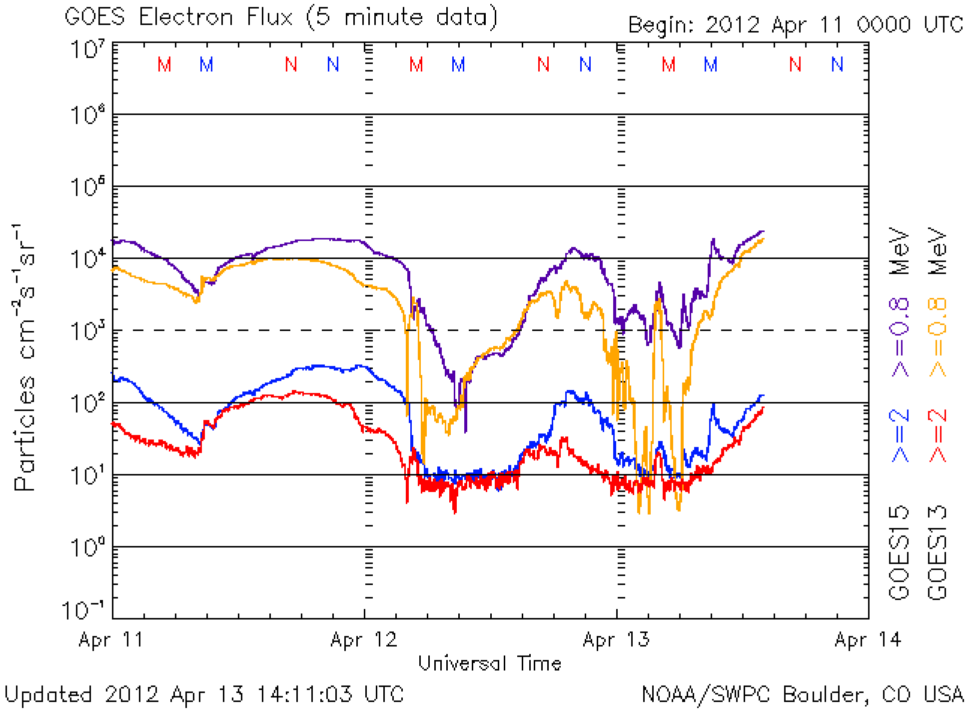




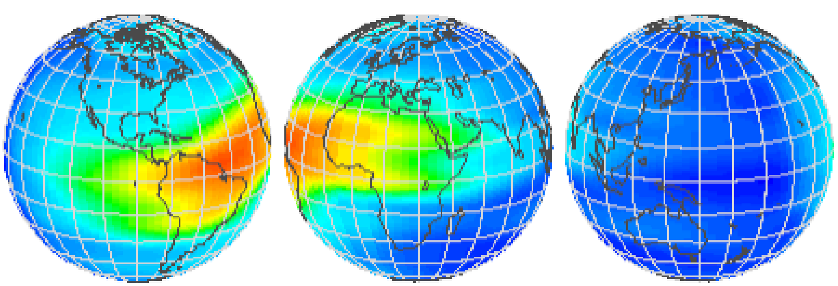
(Real-time ionospheric total electron content)

Note: this is the same interaction responsible for **aurora borealis**

Note: ALL of these sources are extremely **high energy**
(*i.e.*, much higher than we could reasonably generate!)



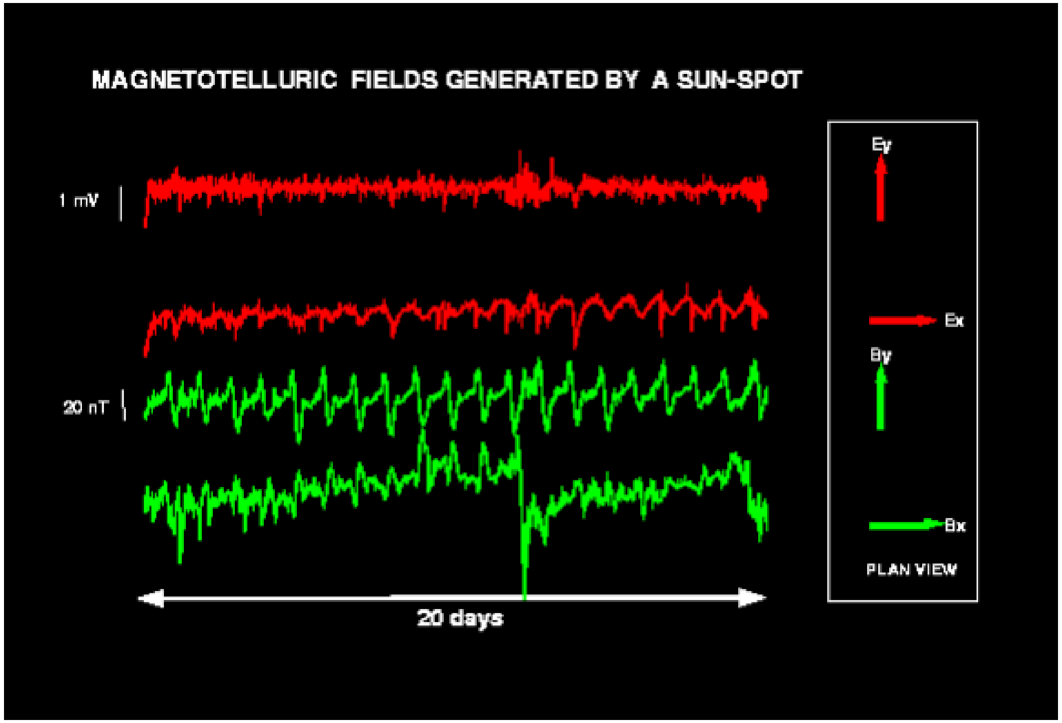
NOAA GOES Electron Flux



USU GAIM Total Electron Content

"Space weather", or flux of high-energy charged particles & electrons, is also of practical Interest because of effects on satellites (electron flux greater than some threshold can induce charge on satellite electronics – discharge has fried a few Communications satellites)

Example effect of a sunspot. The repeating signal (strongest in E_x and H_y) is the diurnal variation as Earth rotates within the solar wind. The large departure in H_x ~ day 12 is a sunspot.



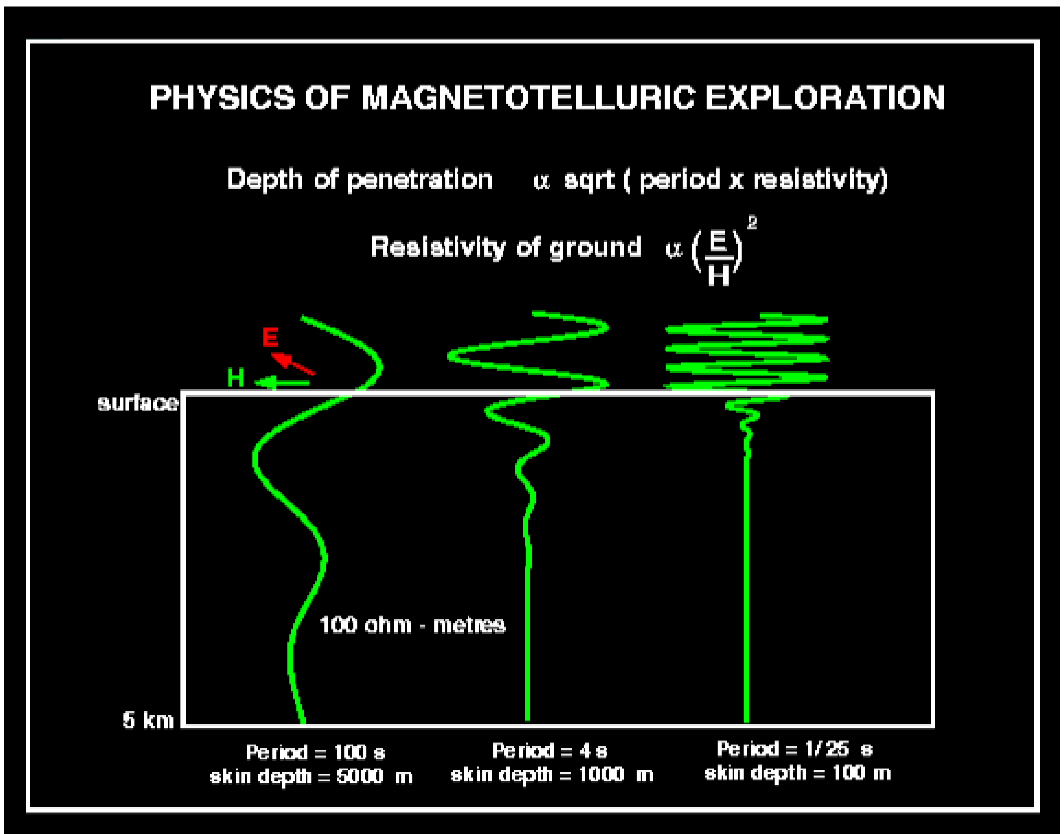
This example gave resistivity constraint to depths of a few 100 km!

Magnetotelluric (MT) Theory

For a sine wave, $\sin(\omega t)$,

$$E \sin(\omega t) \; \mu \; \sqrt{\rho_{sd}} \, H \sin(\omega t)$$

where ρ_{sd} is an averaged resistivity over the “skin depth” (depth of significant penetration of the electric field $\boldsymbol{E}$ and magnetic field $\boldsymbol{H}$)



Magnetotelluric (MT) Theory

***Electromagnetic Induction* in *the Half – Space*:**

We start from *the Faraday – Maxwell* and *the Ampere – Maxwell laws*:

$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}; \qquad \text{and} \qquad \vec{\nabla}\times\vec{B} = \mu\sigma\vec{E} + \mu\epsilon\frac{\partial\vec{E}}{\partial t}. \qquad (1a)$$

Further, we assume: $\nabla\cdot\vec{B} = 0$, [*i.e., Gauss' Law, since* $\vec{H} \approx \vec{B}$, *with* $(\mu M) \ll B$ *for bulk crust*]; &

$$\nabla\cdot\vec{E} = 0, \; [\textit{bulk crust is electrically neutral}] \qquad (1b)$$

Taking the curl of both expressions in $(1a)$:

$$\vec{\nabla}\times(\vec{\nabla}\times\vec{E}) = \vec{\nabla}(\vec{\nabla}\cdot\vec{E}) - \nabla^2\vec{E} = \vec{\nabla}\times\left(-\frac{\partial\vec{B}}{\partial t}\right), \; \&$$

$$\vec{\nabla}\times(\vec{\nabla}\times\vec{B}) = \vec{\nabla}(\vec{\nabla}\cdot\vec{B}) - \nabla^2\vec{B} = \vec{\nabla}\times\left[\mu\sigma\vec{E} + \mu\epsilon\frac{\partial\vec{E}}{\partial t}\right].$$

Using $(1b)$, *therefore*:

$$-\nabla^2\vec{E} = -\frac{\partial}{\partial t}(\vec{\nabla}\times\vec{B}) = -\frac{\partial}{\partial t}\left[\mu\sigma\vec{E} + \mu\epsilon\frac{\partial\vec{E}}{\partial t}\right] = -\mu\left[\epsilon\frac{\partial^2\vec{E}}{\partial t^2} + \sigma\frac{\partial\vec{E}}{\partial t}\right], \; \&$$

$$-\nabla^2\vec{B} = \mu\left[\sigma(\vec{\nabla}\times\vec{E}) + \epsilon\frac{\partial(\vec{\nabla}\times\vec{E})}{\partial t}\right] = -\mu\left[\epsilon\frac{\partial^2\vec{B}}{\partial t^2} + \sigma\frac{\partial\vec{B}}{\partial t}\right].$$

Approximating $\vec{B}$ *by* $\vec{H}$, from $(1b)$, and *simplifying*, *we get the governing* ***Wave Equation pair***:

$$\nabla^2\vec{E} = \mu\left[\epsilon\frac{\partial^2\vec{E}}{\partial t^2} + \sigma\frac{\partial\vec{E}}{\partial t}\right], \quad \& \quad \nabla^2\vec{H} = \mu\left[\epsilon\frac{\partial^2\vec{H}}{\partial t^2} + \sigma\frac{\partial\vec{H}}{\partial t}\right]. \qquad (1c)$$

Magnetotelluric (MT) Theory

Fourier transformation of these wave equations, assuming a solution of the form $e^{i\omega t}$, *we get:*

$$\nabla^2\vec{E} + k^2\vec{E} = 0, \quad \& \quad \nabla^2\vec{H} + k^2\vec{H} = 0, \quad (\textit{Helmholtz Equations}), \quad \textit{with} \quad k^2 = \mu[\epsilon\omega^2 - i\sigma\omega]. \qquad (1d)$$

But for Earth materials and frequencies less than 100 kHz, $\epsilon\omega^2 \ll i\sigma\omega$, and $k^2 \approx i\mu\sigma\omega$. In this case, The above pair of equations reduce to the respective ***Diffusion equations*:**

$$\nabla^2\vec{E} = \mu\sigma\frac{\partial\vec{E}}{\partial t}, \quad \& \quad \nabla^2\vec{H} = \mu\sigma\frac{\partial\vec{H}}{\partial t}. \qquad (1e)$$

Assuming solutions of the form e^{-ikz}, because Earth does not generate EM-energy, and the fields must vanish at the Earth's surface (z=0), the solutions simplify to:

$$\vec{E} = E_0 e^{-ikz}, \quad \& \quad \vec{H} = H_0 e^{-ikz}, \quad \text{where we define a skin-depth,} \quad \delta = \frac{1}{\Re\,\boldsymbol{k}} = \sqrt{\frac{2}{\mu\sigma\omega}} = \sqrt{\frac{2\rho}{\mu\omega}} \qquad (1f)$$

* Given that the distance from the source of the induced field to the Earth's surface is large, the induced magnetic field only has horizontal components $\Rightarrow$ $\boldsymbol{H_z = 0}$.

* Also, since this horizontal magnetic field propagates downward as per the solution, (1f), the induced electric field CANNOT have a vertical component $\Rightarrow$ $\boldsymbol{E_z = 0}$.

So, by Faraday's Law, since:

$$\left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z}\right) = -\frac{\partial H_x}{\partial t}, \quad \left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right) = -\frac{\partial H_y}{\partial t}, \quad \& \quad \left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right) = -\frac{\partial H_z}{\partial t}, \qquad (1g)$$

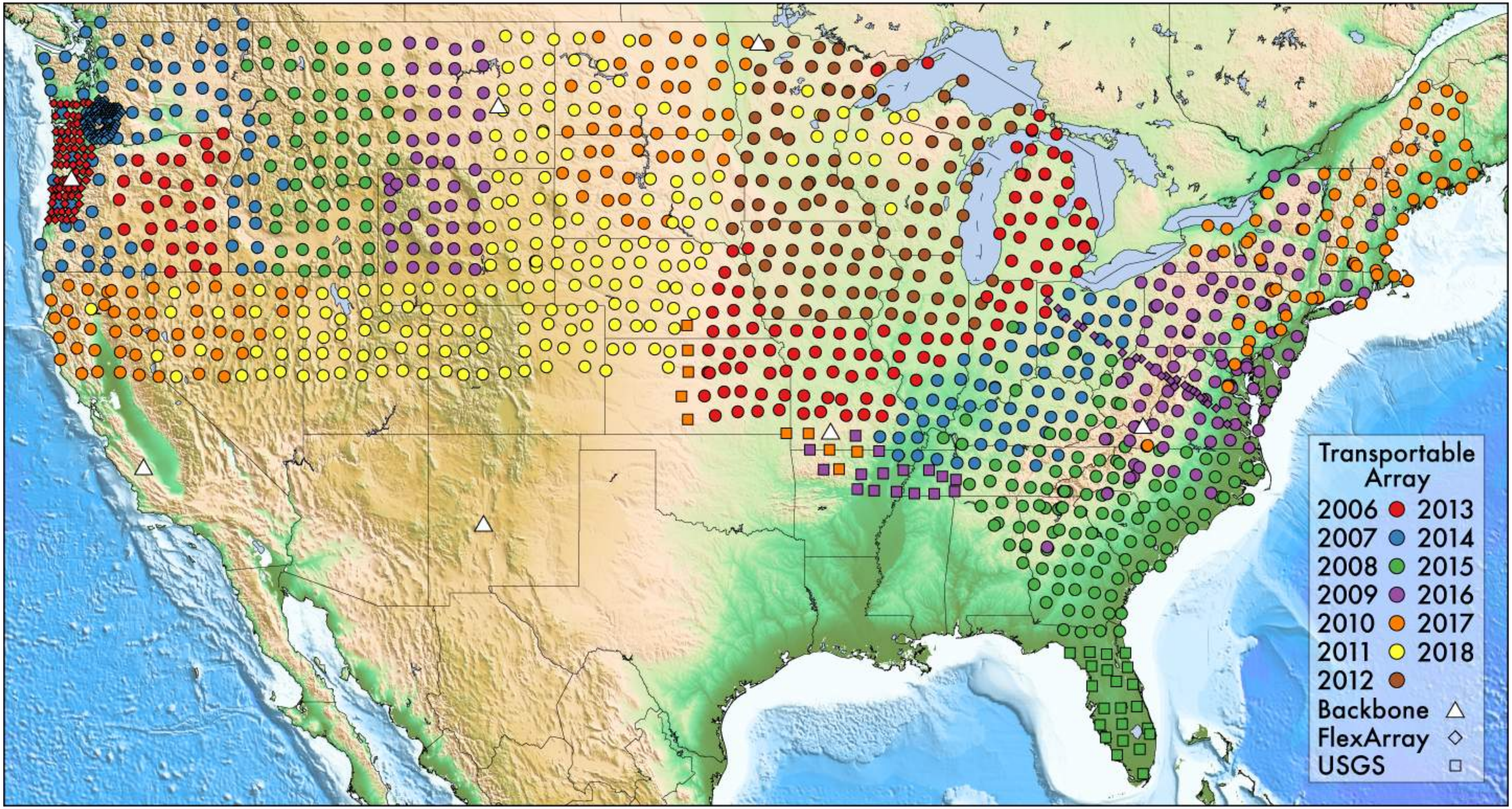
we can deduce that,

$$\boldsymbol{\frac{\partial E_y}{\partial x} = 0 = \frac{\partial E_x}{\partial y}}, \quad \& \quad \boldsymbol{\frac{\partial E_y}{\partial z} = \frac{\partial H_x}{\partial t}}, \quad \& \quad \boldsymbol{\frac{\partial E_x}{\partial z} = -\frac{\partial H_y}{\partial t}}, \qquad (1h)$$

therefore,

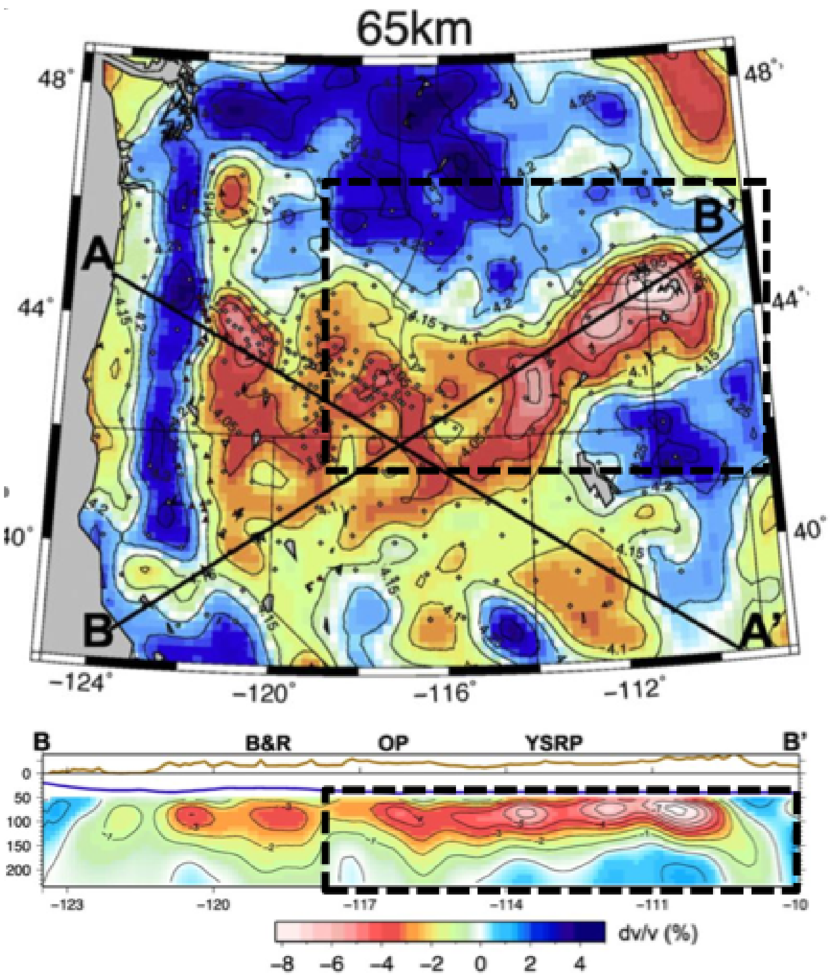
$$-\boldsymbol{k}E_{y0}e^{-\boldsymbol{k}z} = i\omega H_{x0}e^{-\boldsymbol{k}z}, \quad \& \quad \textit{thus}, \quad |Z_{yx}(\omega)|^2 = \left(\frac{E_{y0}}{H_{x0}}\right)^2 = \frac{\omega}{\mu\sigma} = \frac{\omega\rho}{\mu} = \left(\frac{E_{x0}}{H_{y0}}\right)^2 = = |Z_{xy}(\omega)|^2 \qquad (1i)$$

US-Array: MT array deployment for EarthScope



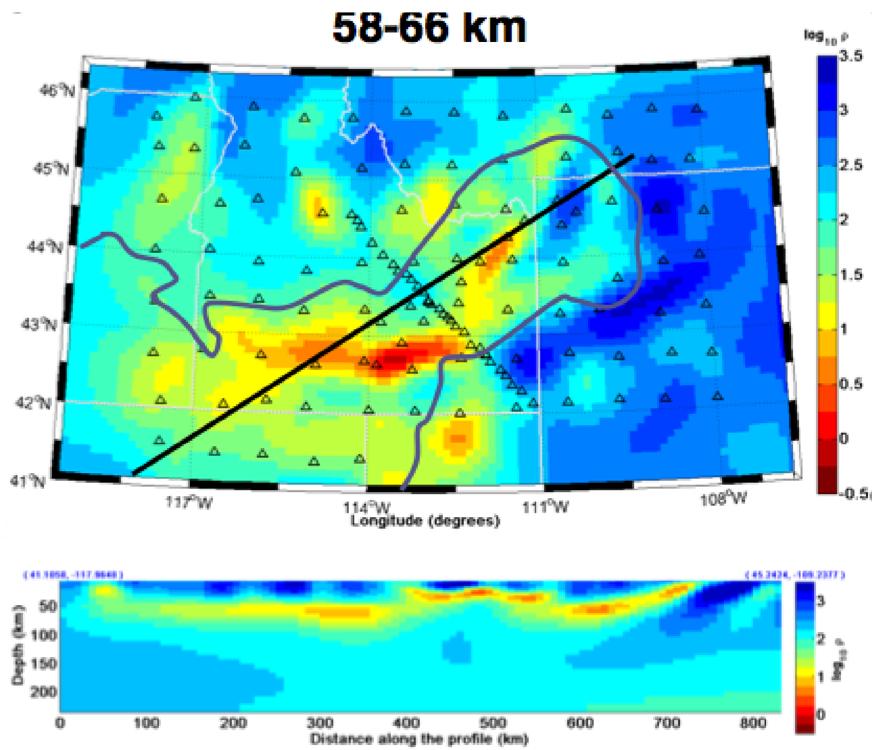
Yellowstone-Snake River Plain System:

Seismic V_s (Rayleigh wave tomo)

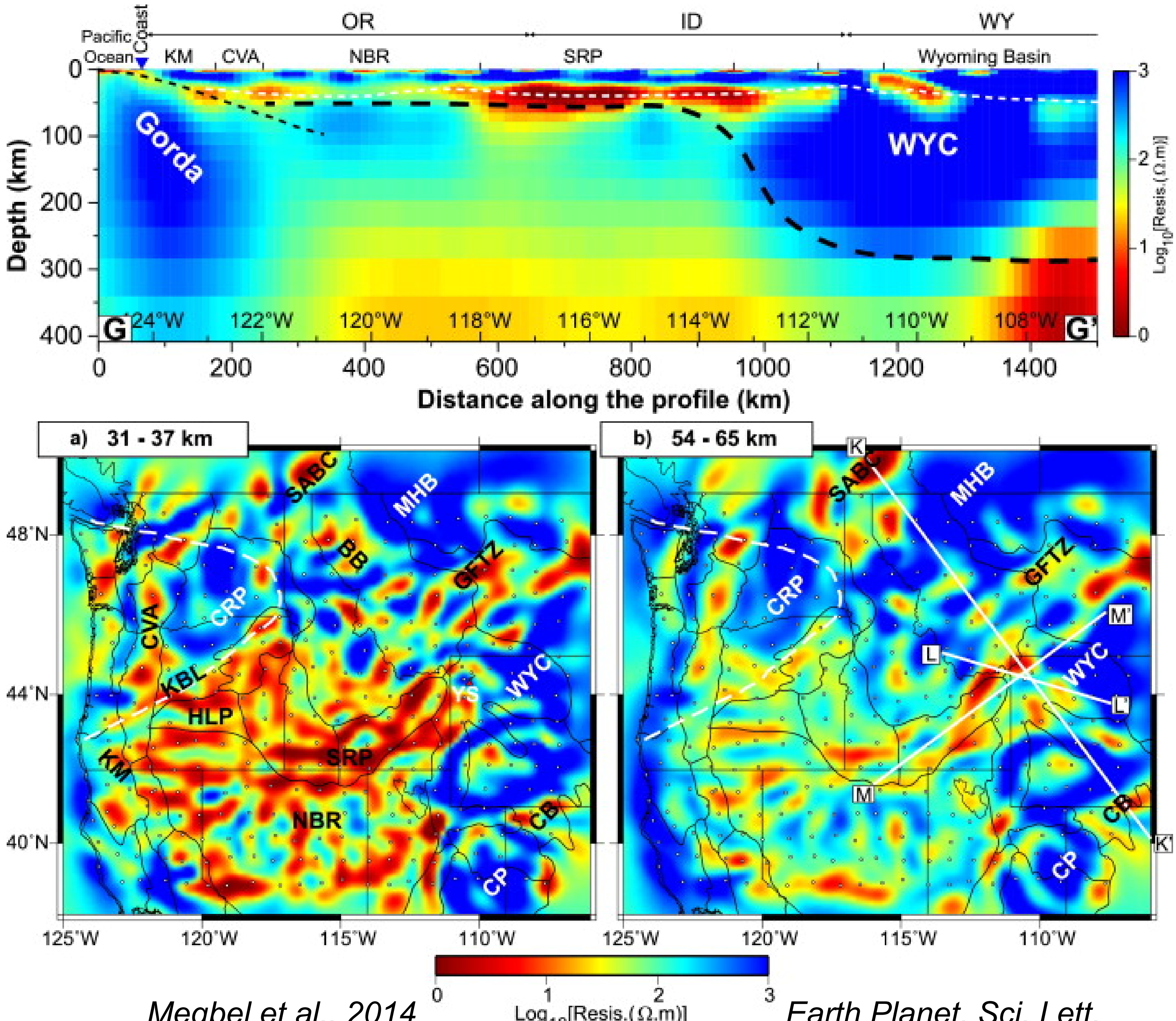


Wagner et al., EPSL 2010

Electrical Resistivity ρ



Kelbert et al., 2011



Meqbel et al., 2014 *Earth Planet. Sci. Lett.*

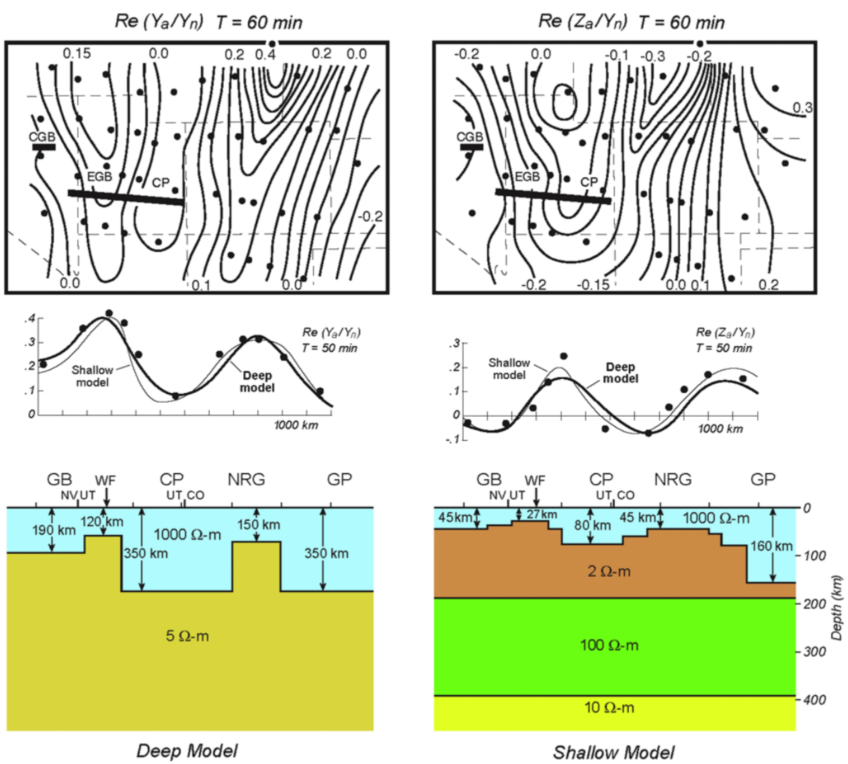


Figure 4. (top) Anomaly maps of horizontal (Y) and vertical (Z) magnetic field variations at a period of 60 min for Great Basin and Colorado Plateau regions. (middle) Anomaly profiles at 50 min period for the line of MV stations closest to our transect. Y_{ia}/Y_n refers to in-phase anomalous horizontal field normalized by external inducing field, while Z_{ia}/Y_n refers to normalized in-phase anomalous vertical field. (bottom) Alternate 2-D model views derived by trial-and-error forward fitting of MV profile data, which provide nearly equivalent fits (middle). Horizontal black rectangles are locations of modern, dense MT profiles of *Wannamaker et al.* [1997a] in the central Great Basin (CGB), plus the current profile across the eastern GB and the CP. Wasatch Front is WF. Redrawn after *Porath et al.* [1970] and *Porath* [1971].

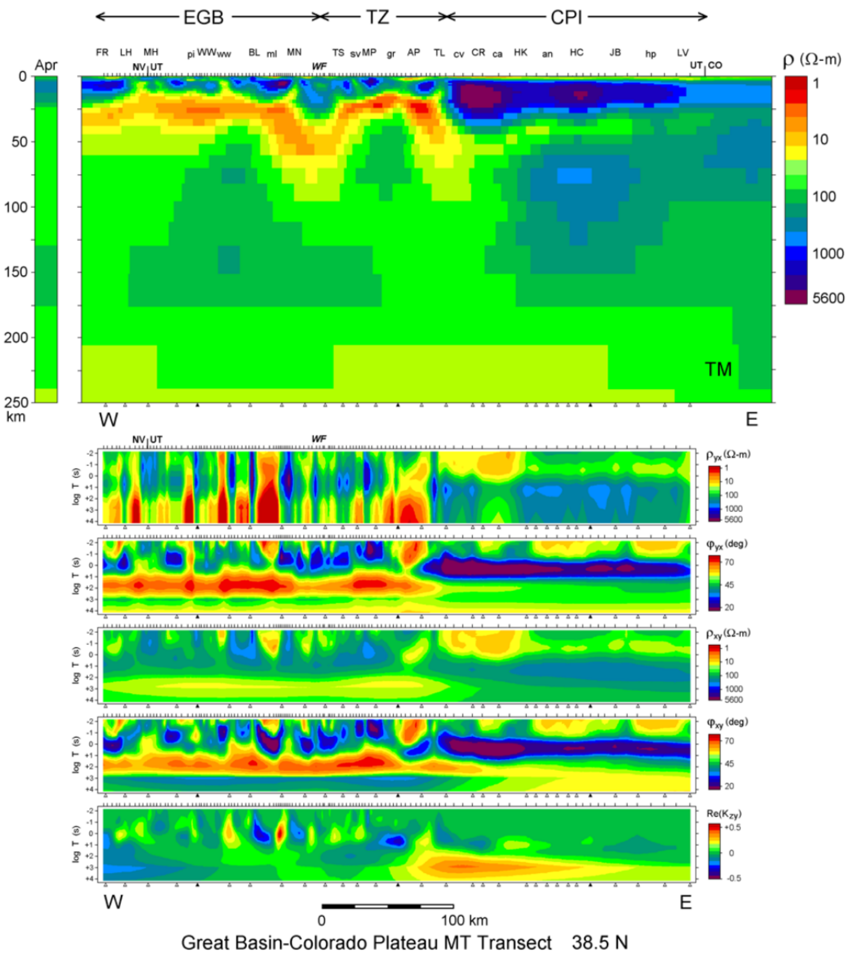
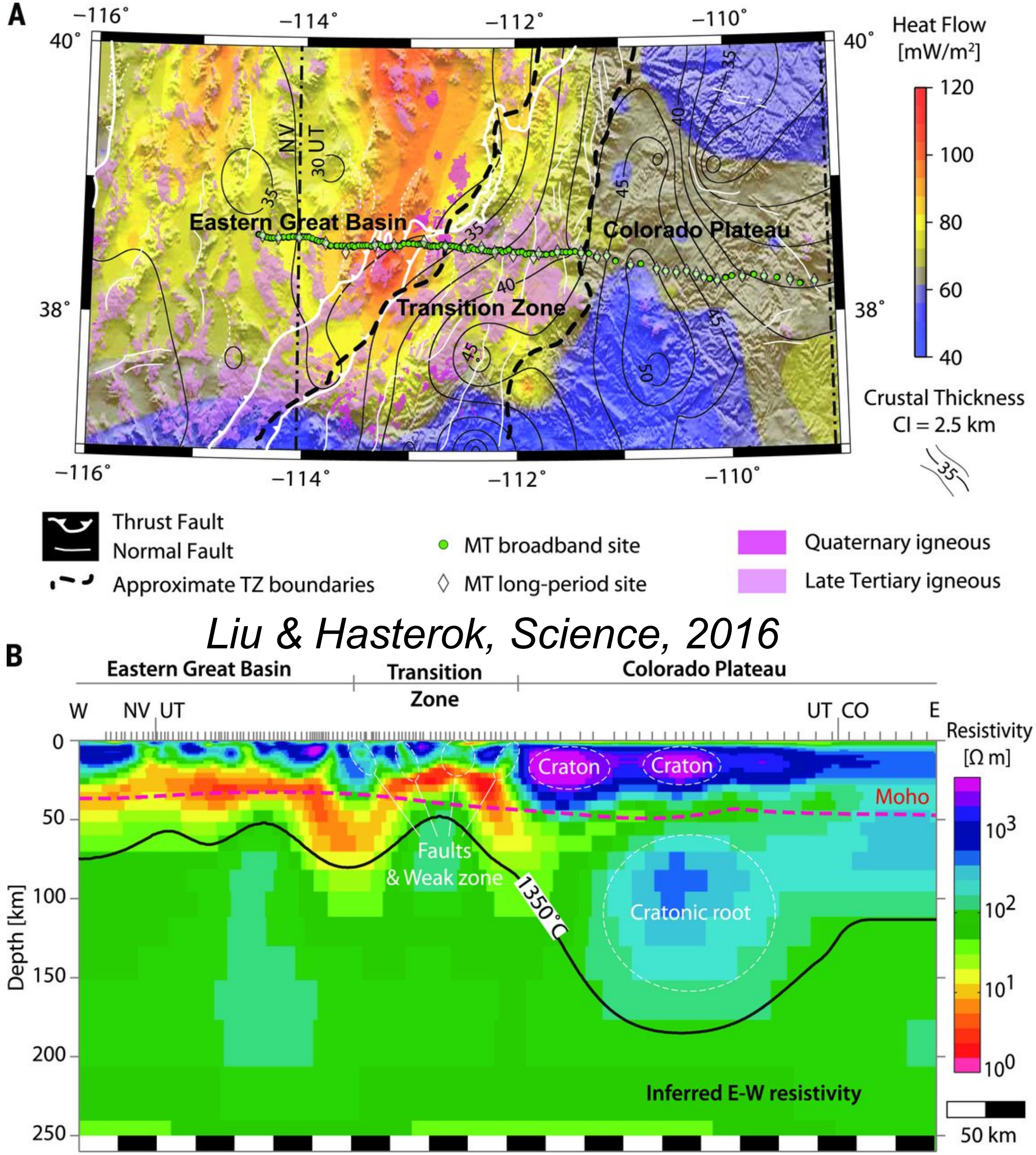


Figure 7. Two-dimensional inversion model of GB-CP transect considering TM mode data only. Computed TM and TE pseudosections are plotted below for comparison to data in Figure 5. Geographic locations and other labeling as in Figure 5.

Wannamaker et al. 2008



Liu & Hasterok, Science, 2016

Resistivity structure a bit south of us here in Logan – from older data & newer Inversion to that on the previous slide.

Research supports a strong relationship between Electrical conductivity and mantle viscosity.

Magnetotelluric (MT) Method

Currently, the MT method is more commonly used in large scale studies of tectonics, melts and fluid flux.

EarthScope data show evidence of (primarily E-W trending) small-scale melt bodies under W-C Snake River Plain and widespread melt or graphite in lower crust of the Basin-Range province!

Some (minor but growing) applications in oil & mining; Likely to grow in usage in the future (most probably with the aid of active source)