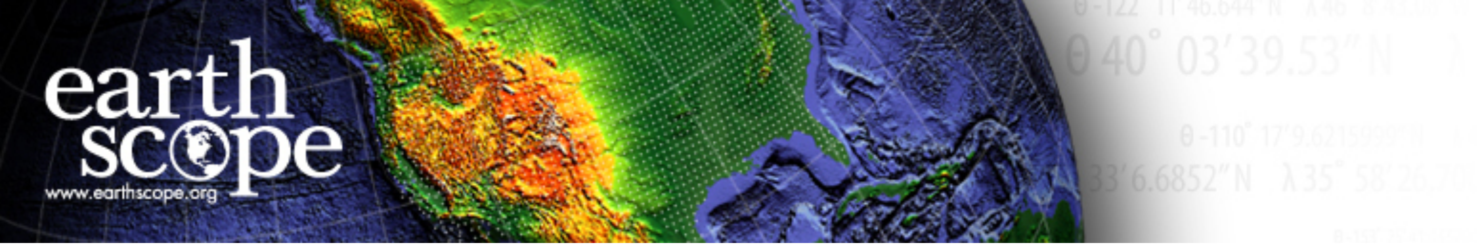
Insights into fluids and melt in the crust and mantle from 3D Inversion of EarthScope MT Data

Gary D. Egbert, Oregon State University



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Deep electrical resistivity structure of the northwestern U.S. derived from 3-D inversion of USArray magnetotelluric data

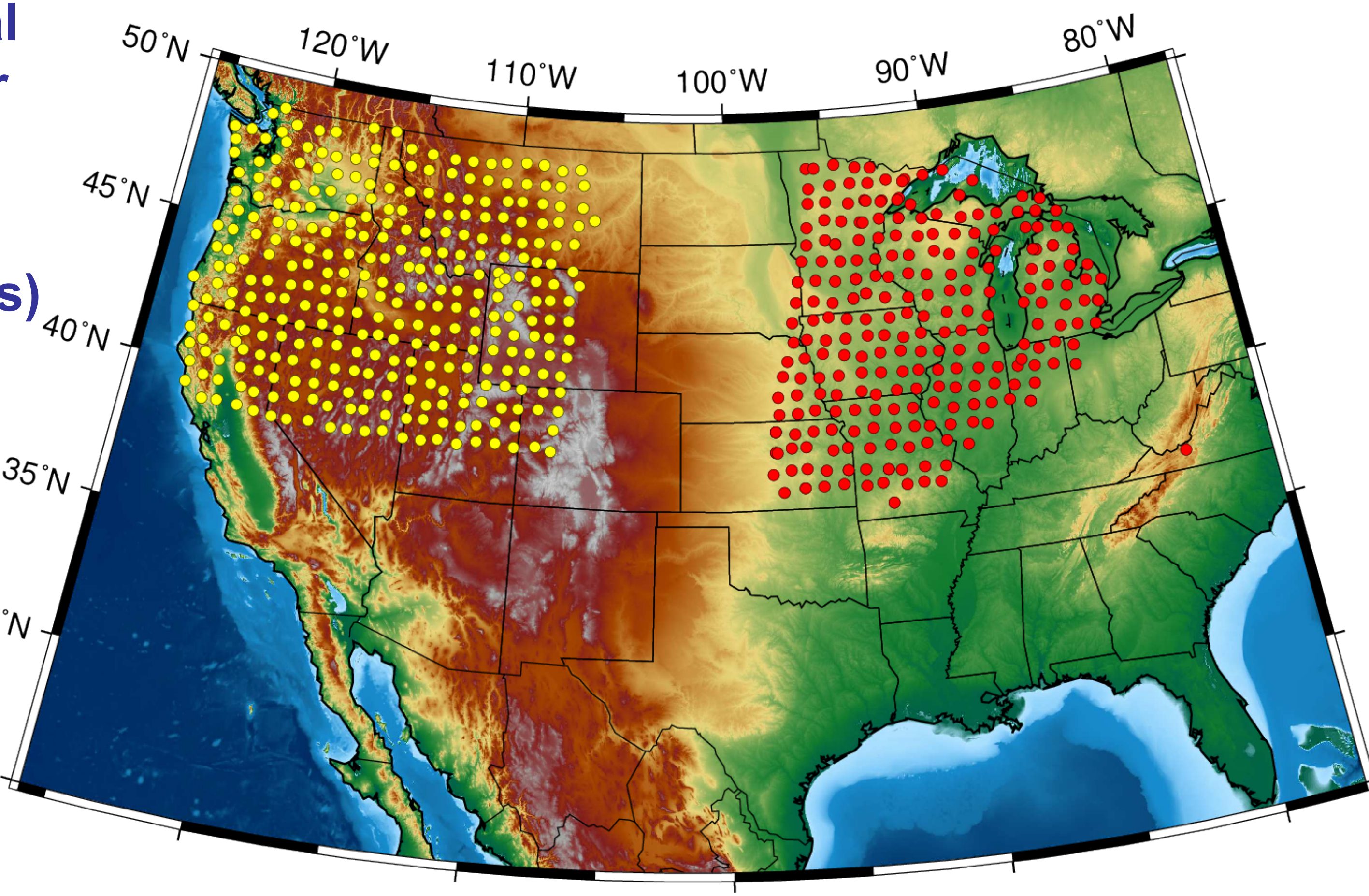
Naser M. Meqbel [a,b,*], Gary D. Egbert [a], Philip E. Wannamaker [c], Anna Kelbert [a], Adam Schultz [a]

MT component of USArray Transportable Array

→70 km nominal spacing, regular grid

→ long period MT (T=10-20000s)

→20-30 day site occupations



NW USA: 325 sites completed 2006-2011

MCR: 235 Sites, 23011-2014

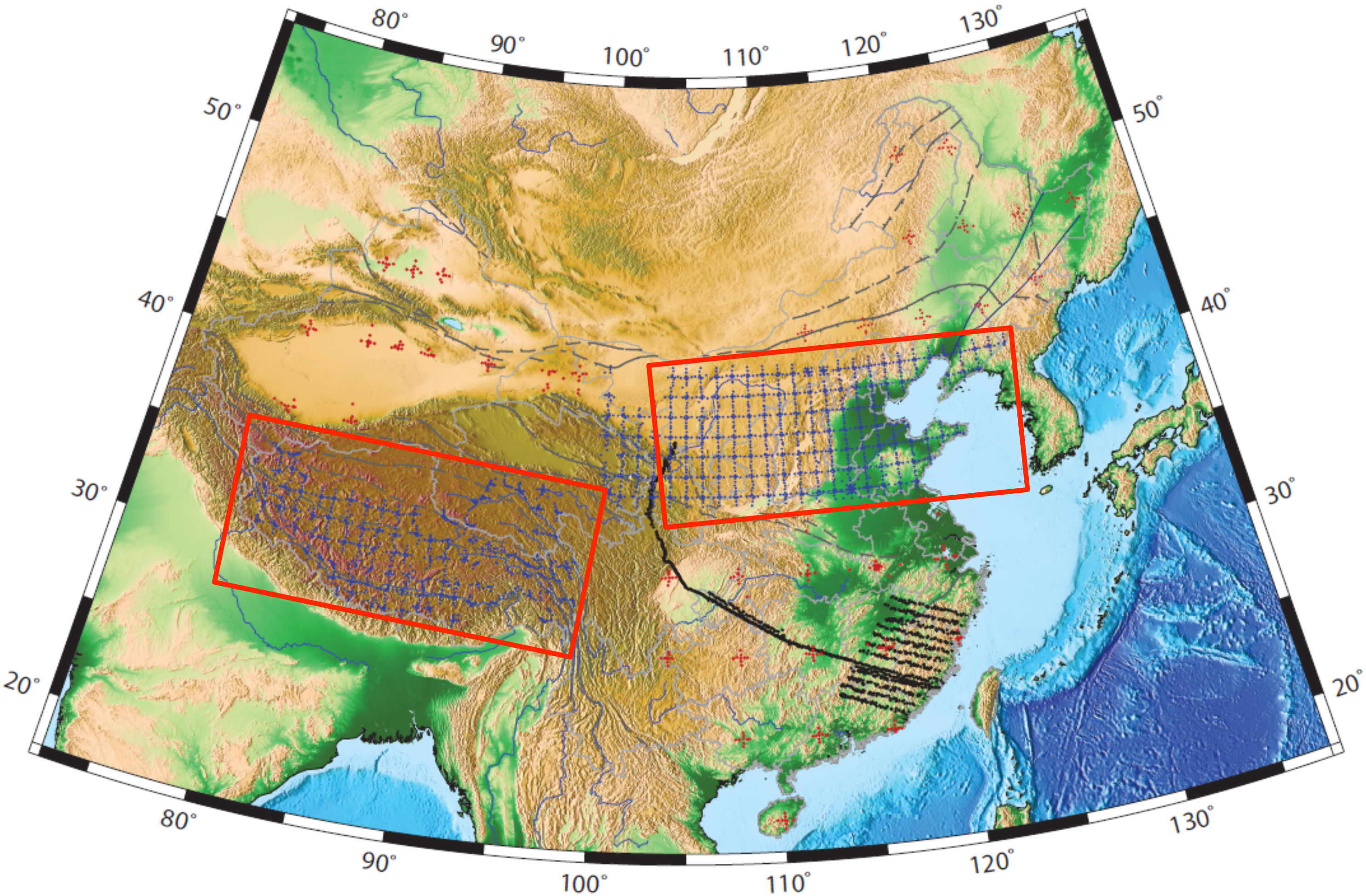
EarthScope MT TA:

- Large spatial scale
- Areal (as opposed to linear) data coverage
- Wide site spacing

Probably the first MT array of this sort

MT Component

- MT component of SinoProbe



SinoProbe-01 PI:
Prof. Wei Wenbo

China University
of Geosciences
(Beijing)

Summary

- ➢MT: some basics, including the standard "2D paradigm"

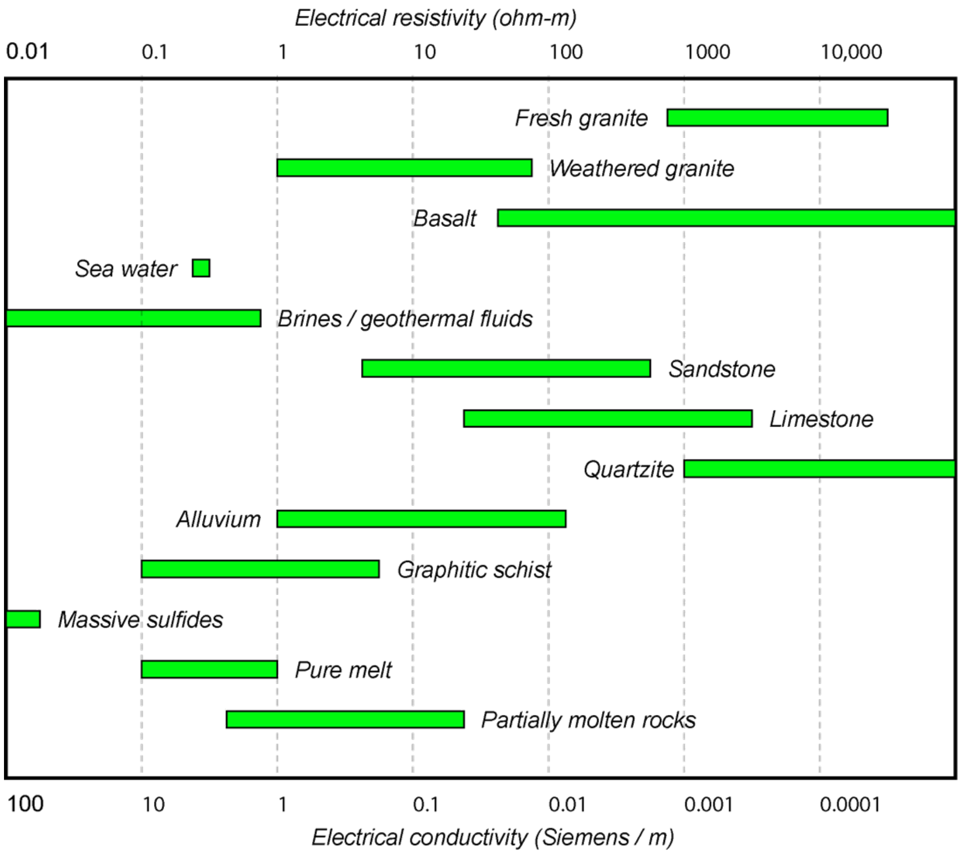
- ➢ Some results from the MT-TA array + 3D inversion approach

  → broad view of high conductivity layers in the lower crust and uppermost mantle

  → large aperture allows resolution of deeper later variations in resistivity (LAB and beyond)

  → conductive sutures record continental assembly

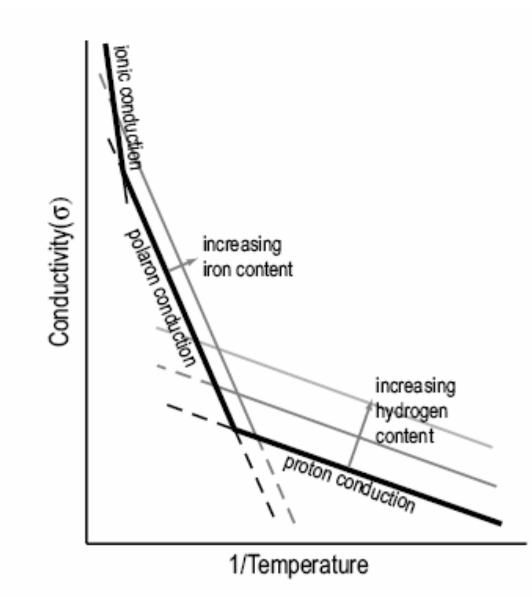
Electrical conductivity of the Earth: why should we care?

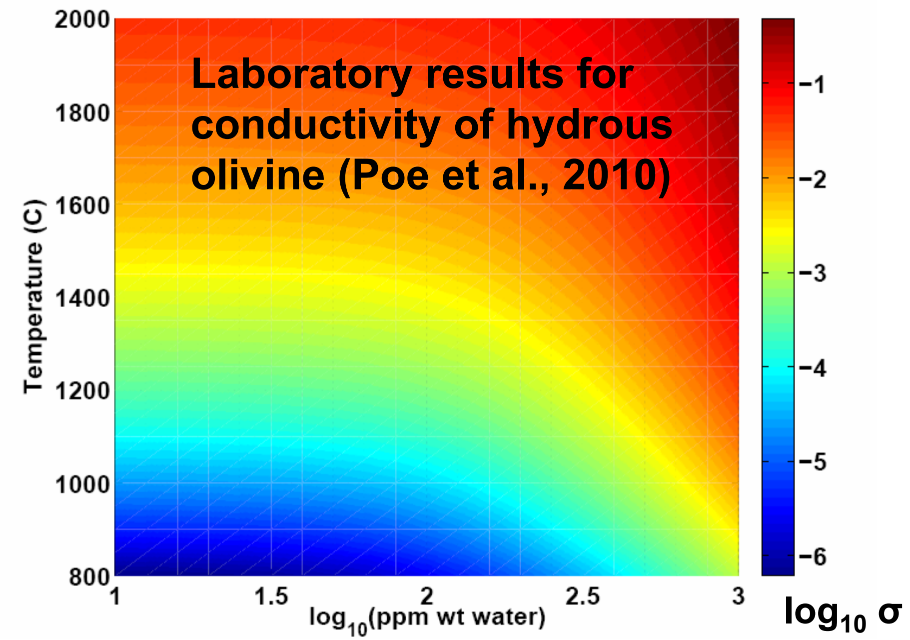


- **Most rock-forming minerals are highly resistive at crustal, upper mantle P-T conditions**
- **Bulk rock conductivity is strongly influenced by the presence and connectivity of fluids (partial melt, water, CO2), volatiles, and a few conductive minerals (sulfides, carbon)**

Texture/interconnection of conductive phase very important (e.g., to anisotropy)

Solid-state conduction in the mantle: thermally activated





Three conduction mechanisms in Olivine:

→Small polaron (Fe^{2+}→Fe^{3+})

→H^+ (water)

→ionic

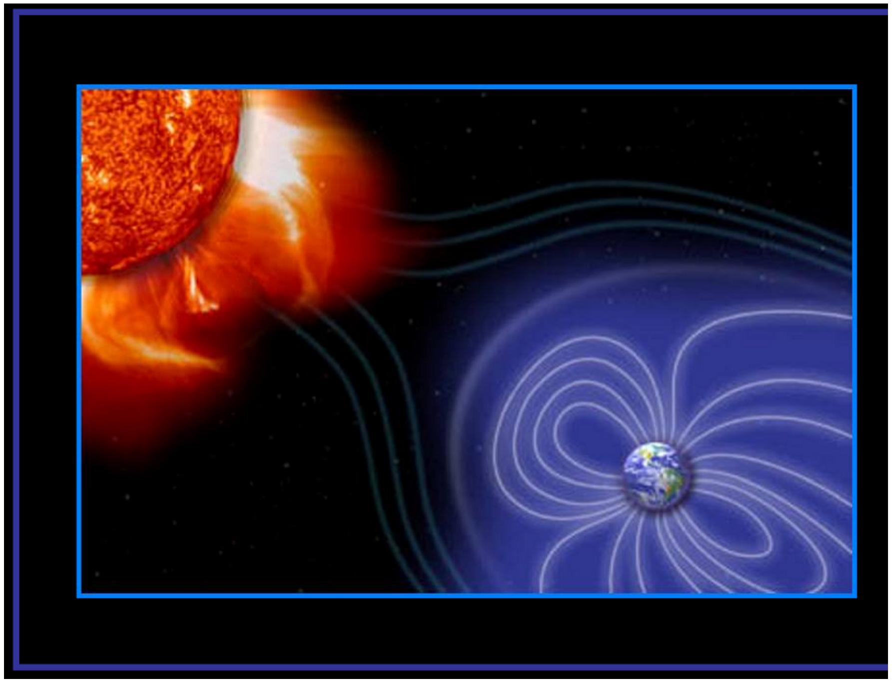
Small amounts of water can increase conductivity of mantle minerals dramatically

Some evidence for anisotropy, but results between labs are not completely consistent

High P-T experiments with hydrous minerals are hard to do!

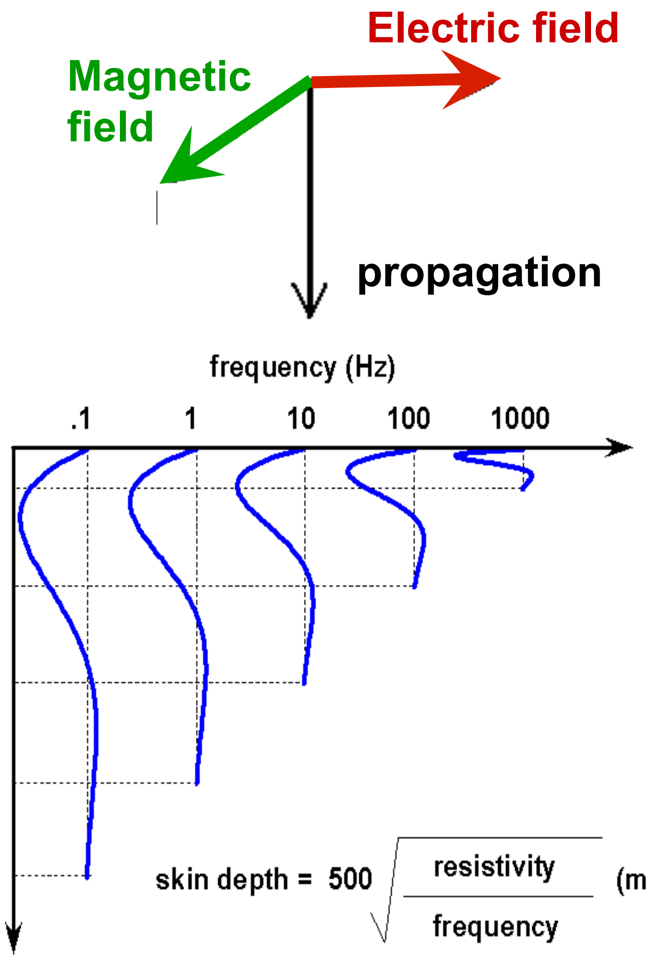
Magnetotellurics (MT)

External magnetic field variations

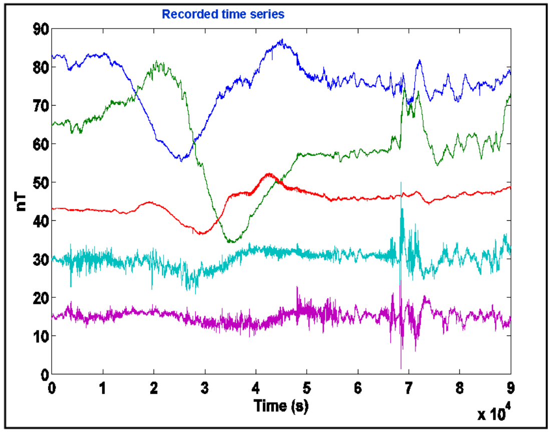


- f > 1 Hz : global lightning
- f < 1 Hz : Solar wind-magnetosphere

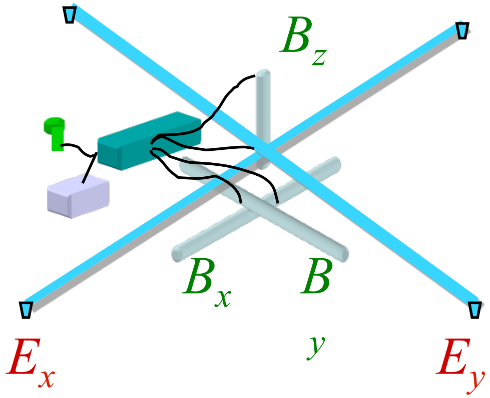
EM fields diffuse into Earth

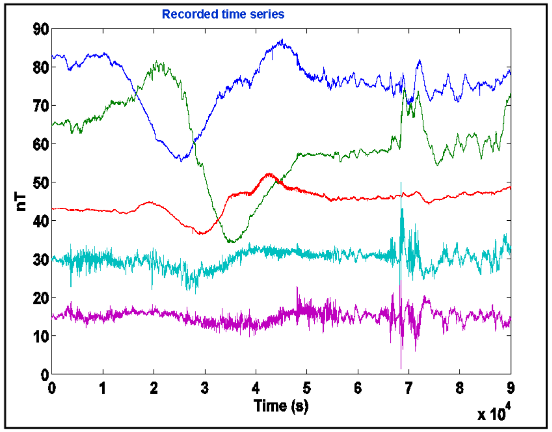


Deeper penetration for lower frequencies, more resistive materials



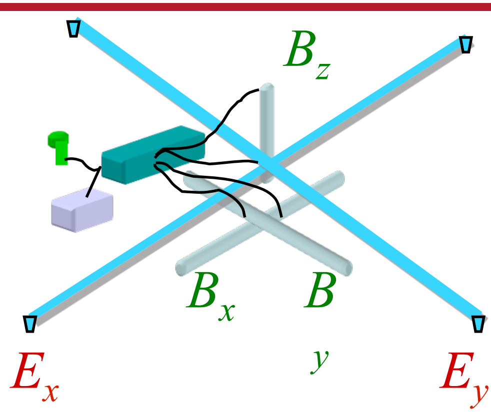
MT: Measure time variations of magnetic and electric field on Earth's surface



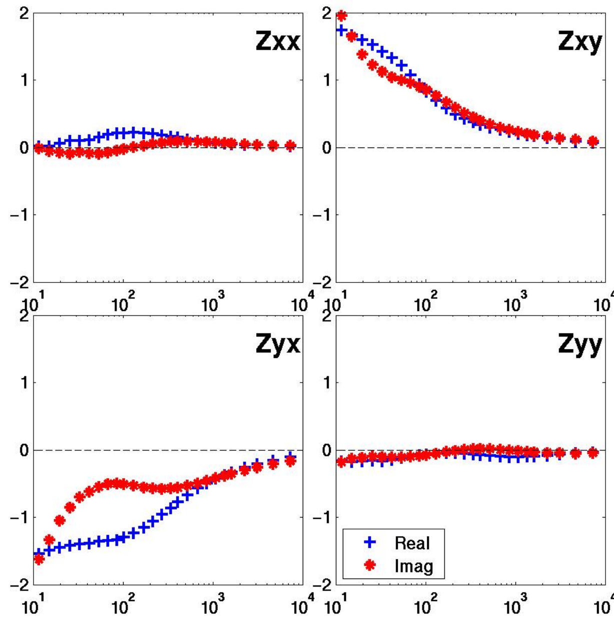


Estimate transfer function relating horizontal magnetic and electric fields

MT: Measure time variations of magnetic and electric field on Earth's surface



$$\begin{bmatrix} \tilde{E}_{xt} \\ \tilde{E}_{yt} \end{bmatrix} =$$



$$\begin{bmatrix} \tilde{B}_{xt} \\ \tilde{B}_{yt} \end{bmatrix}$$

Frequency Domain 2x2 Impedance Tensor

Complex Impedance Tensor

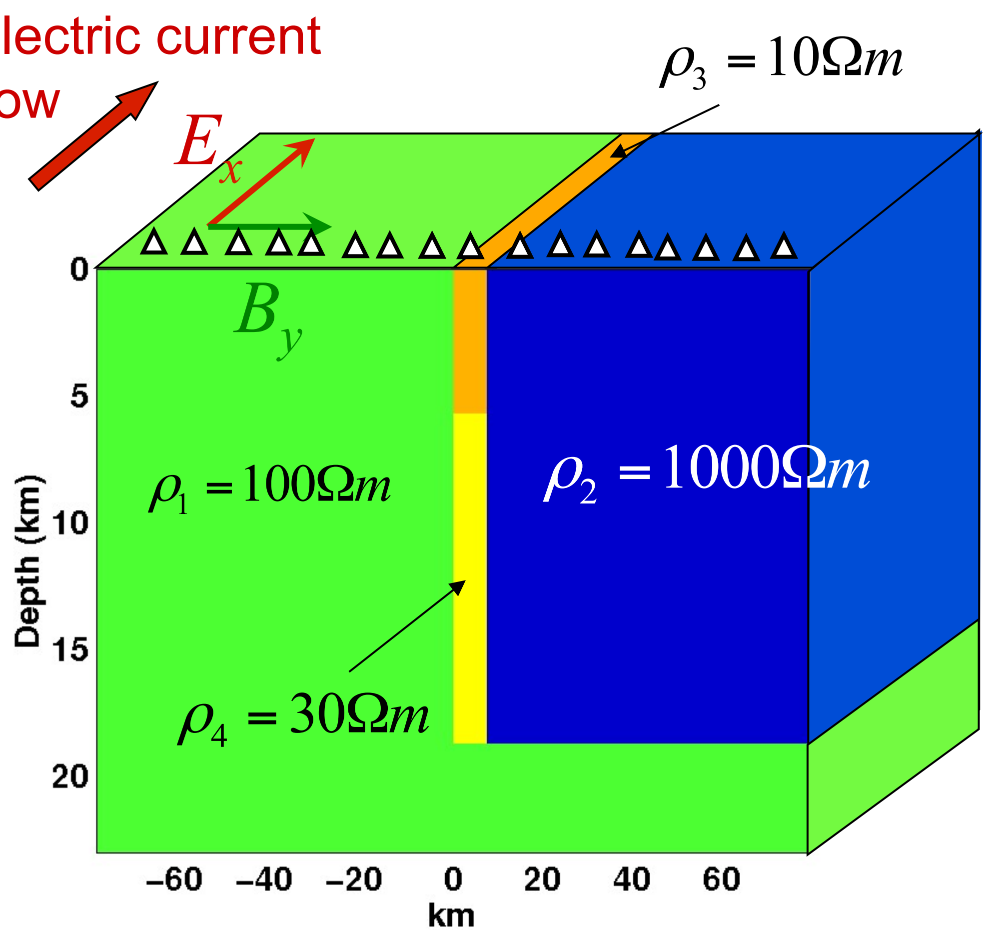
→For 2D case (preferred geologic strike) the tensor will have the special form

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{bmatrix} \begin{bmatrix} B_x \\ B_y \end{bmatrix}$$

When expressed in the proper coordinate system … problem decouples into two "modes" … TE and TM

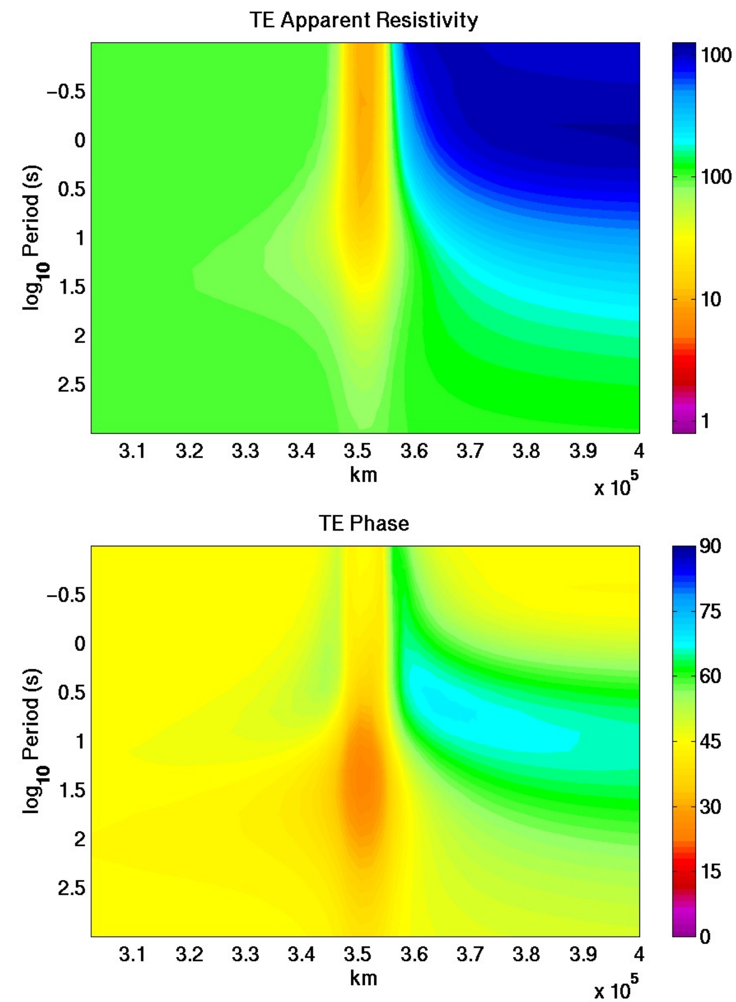
Frequency dependence of impedance amplitude, phase → depth dependence of Earth conductivity

Two-dimensional Earth—e.g., conductive fault zone

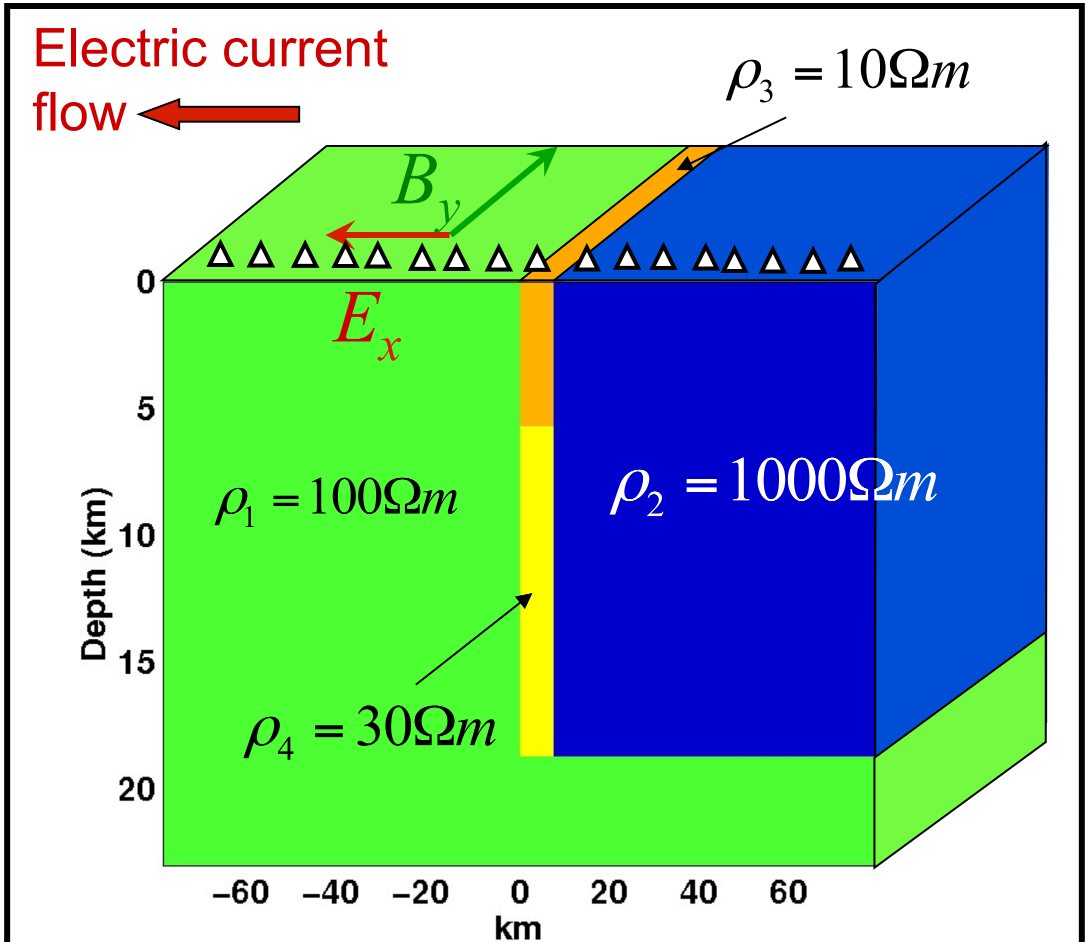


TE mode: Electric currents flow along the geologic strike—magnetic fields are perpendicular

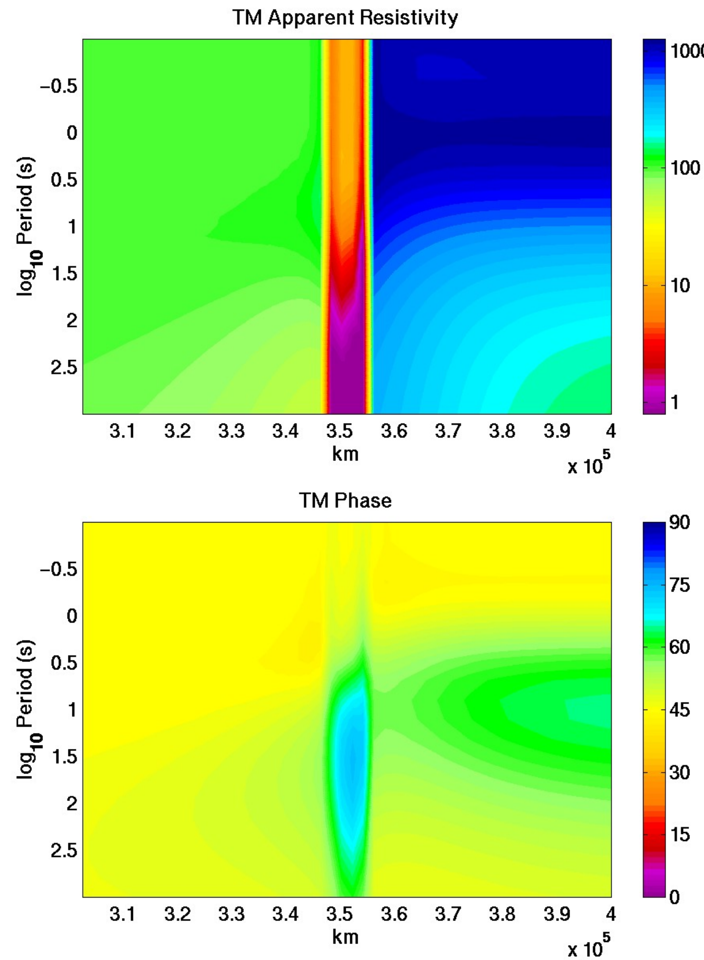
Pseudo-section of r_a, φ for a profile of sites across the fault



Two-dimensional Earth—e.g., conductive fault zone

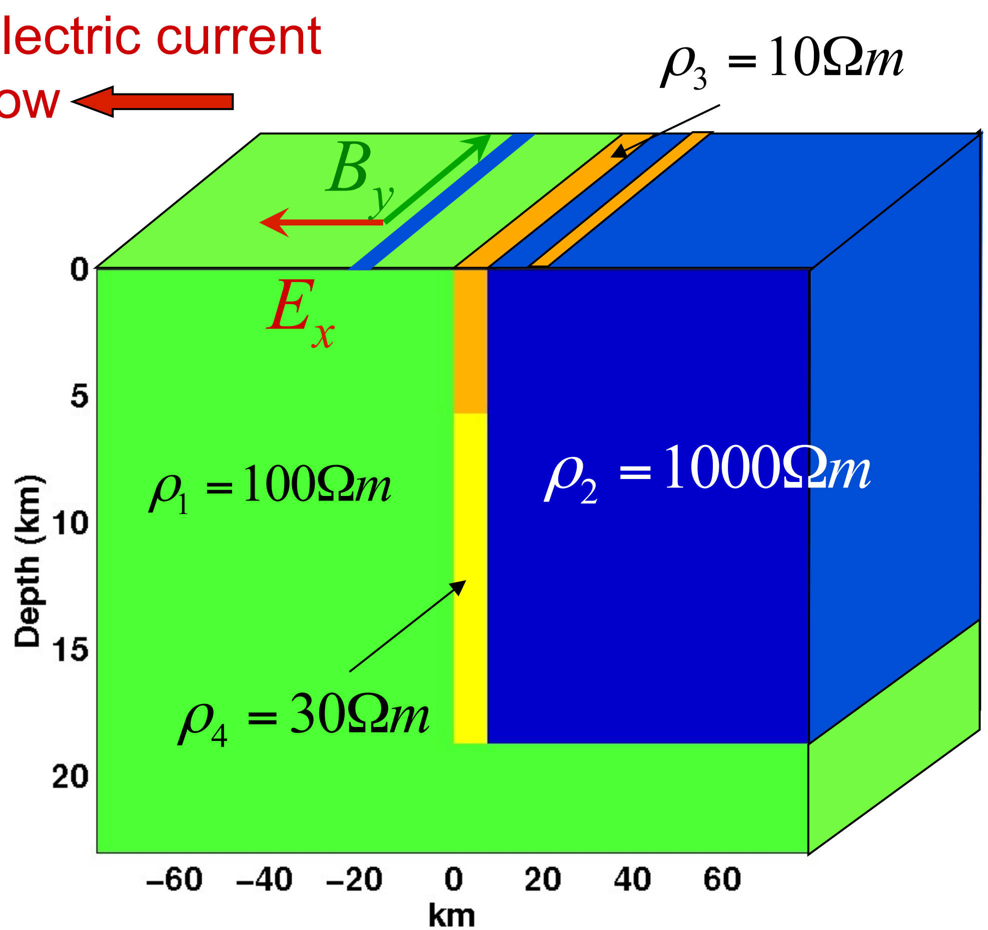


Pseudo-section of r_a, φ for a profile of sites across the fault

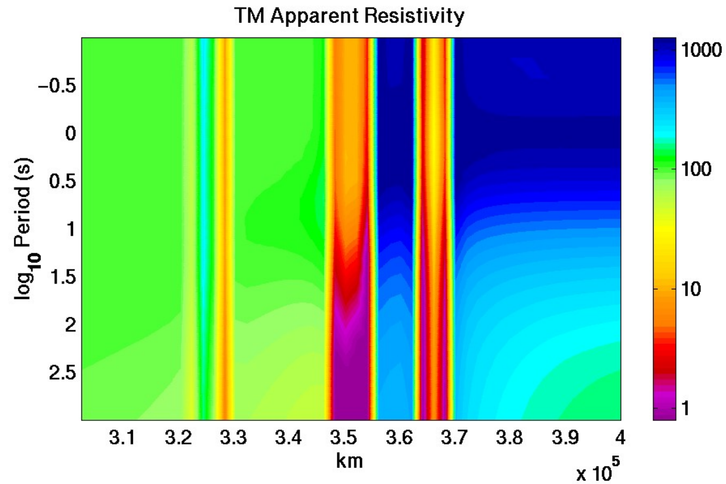


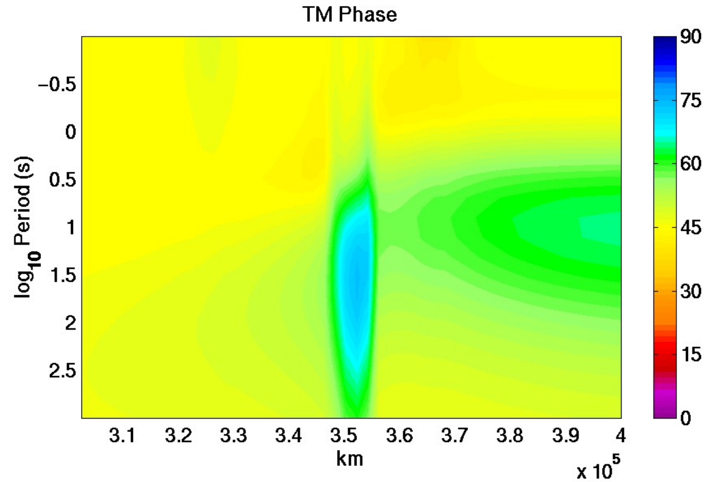
TM mode: Electric currents flow across the geologic strike—magnetic fields are parallel

Two-dimensional Earth—effect of shallow near-surface



Pseudo-section of TM r_a, φ for a profile of sites across the fault



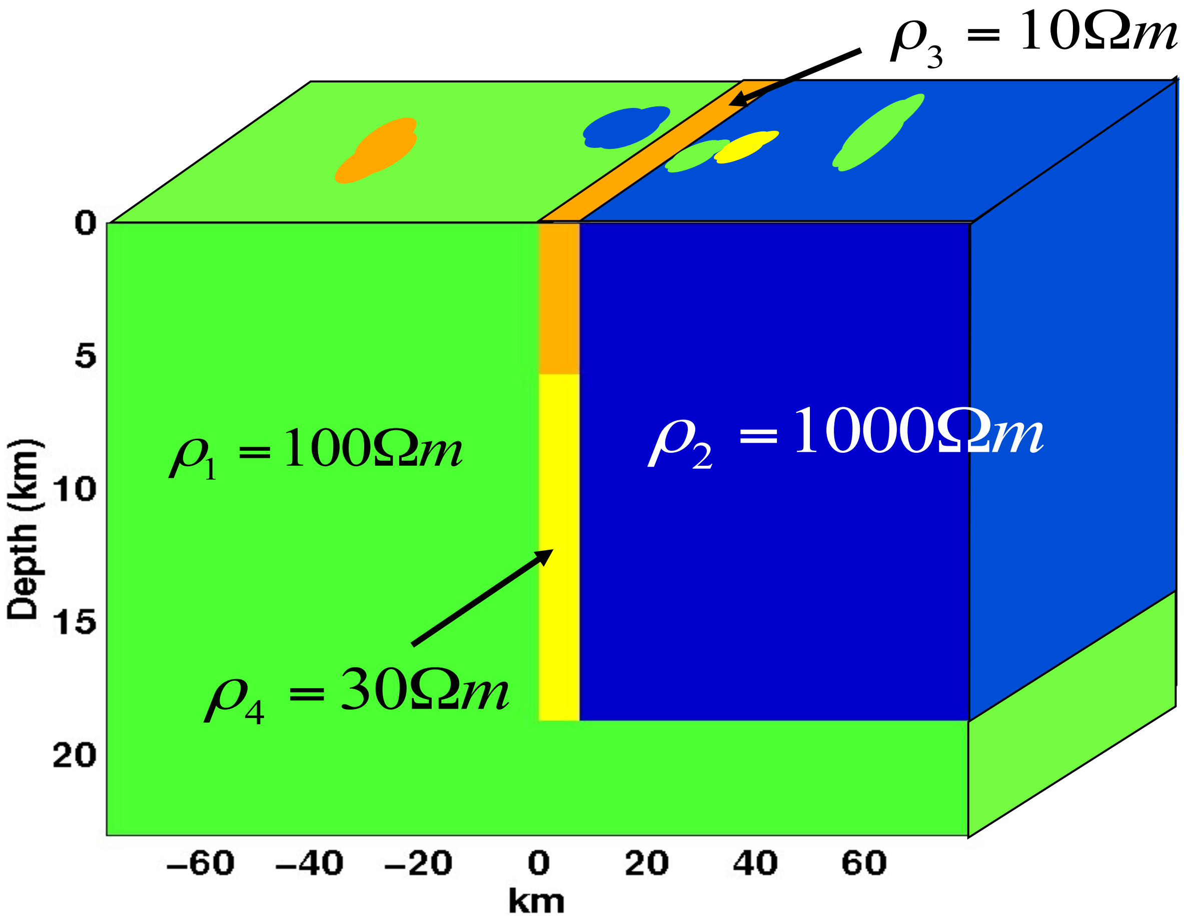


Shallow features distort apparent resistivity at all periods

Phase is not effected!

Two-dimensional Earth—effect of shallow near-surface

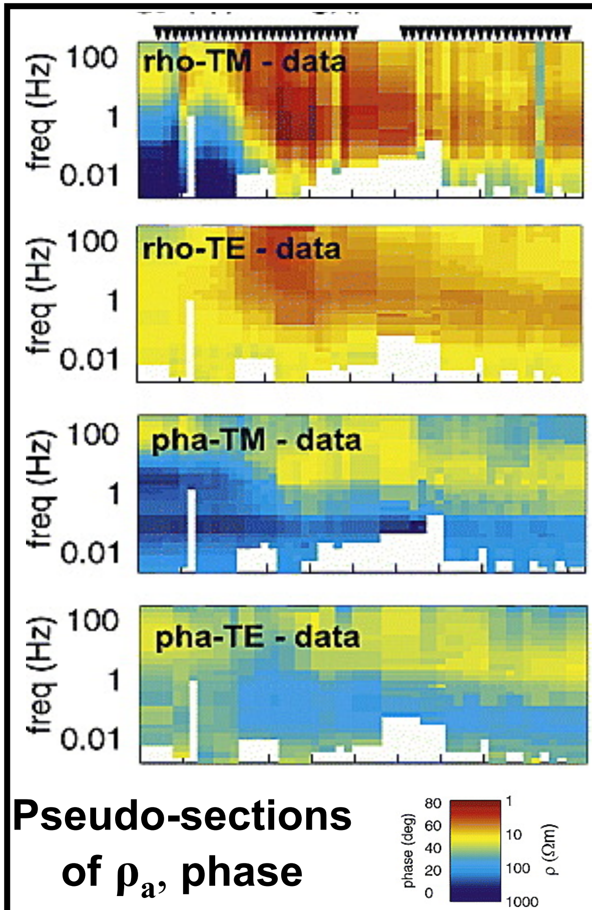
More realistically: even if deep geoelectric structure is 2D, near surface complications would be expected to have a more complicated (3D) geometry



→ Apparent resisitivites for both modes might be distorted at some sites

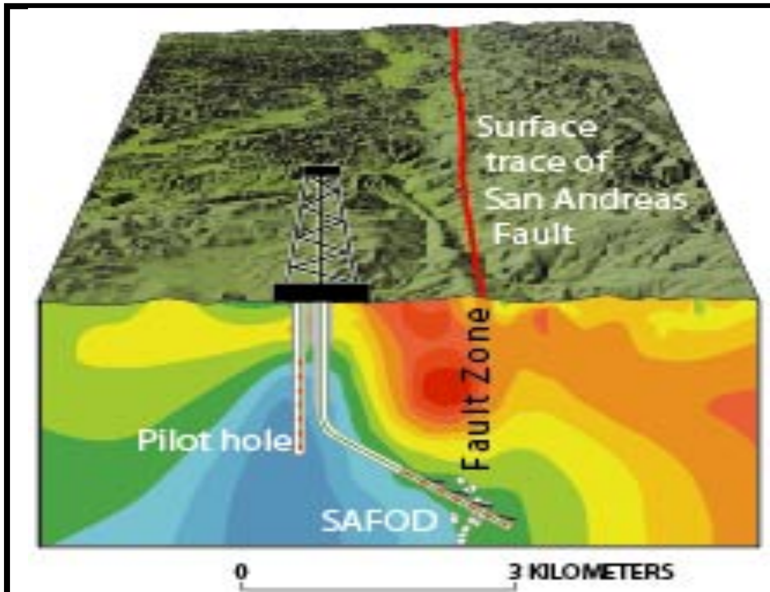
Two-dimensional interpretation of MT profile data

correct coordinate system: only off diagonal impedance components are non-zero → "TE and TM modes"



Pseudo-sections of ρ_a, phase

- **analyze impedance *tensors*—*find "most 2D" strike direction***
- **assess near surface effects**
- **invert for resistivity (emphasize TM , maybe TE phase)**

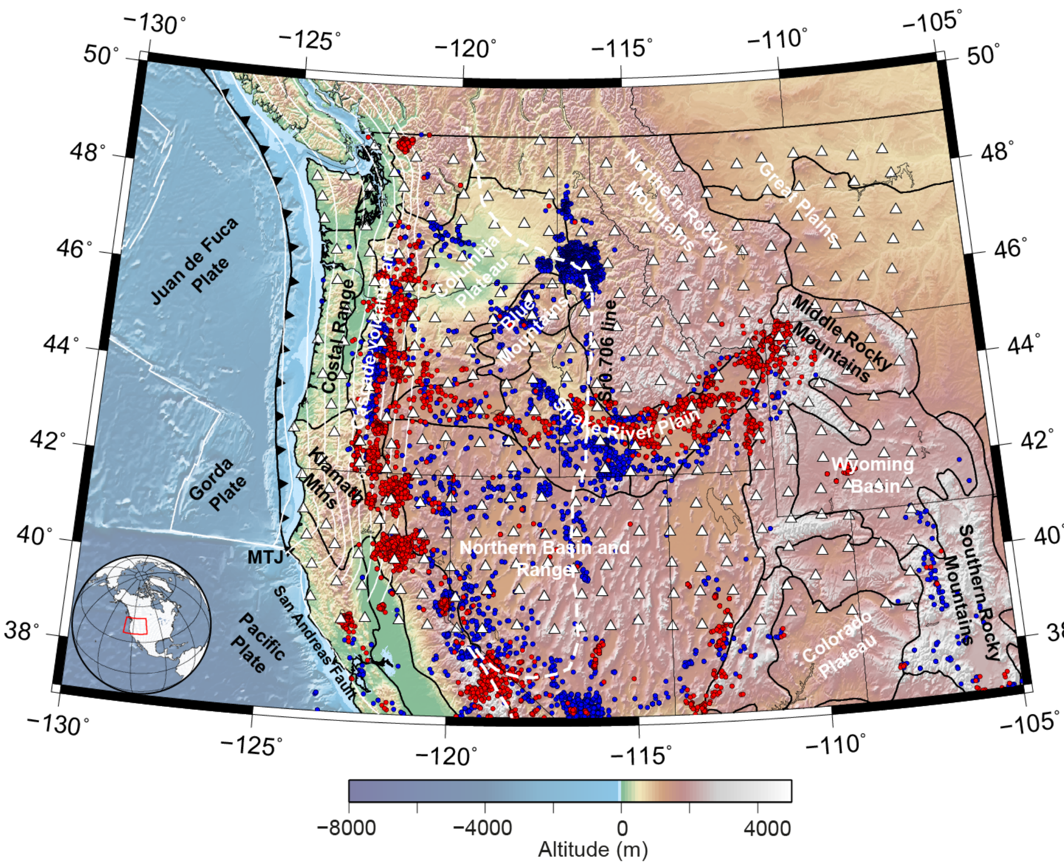


High resolution MT *profiles* across the San Andreas Fault (Unsworth, Bedrosian, et al.)

earth scope
www.earthscope.org

MT TA data from 2006-20011

- 325 stations
- ~70 km site spacing
- T = 10-20,000s

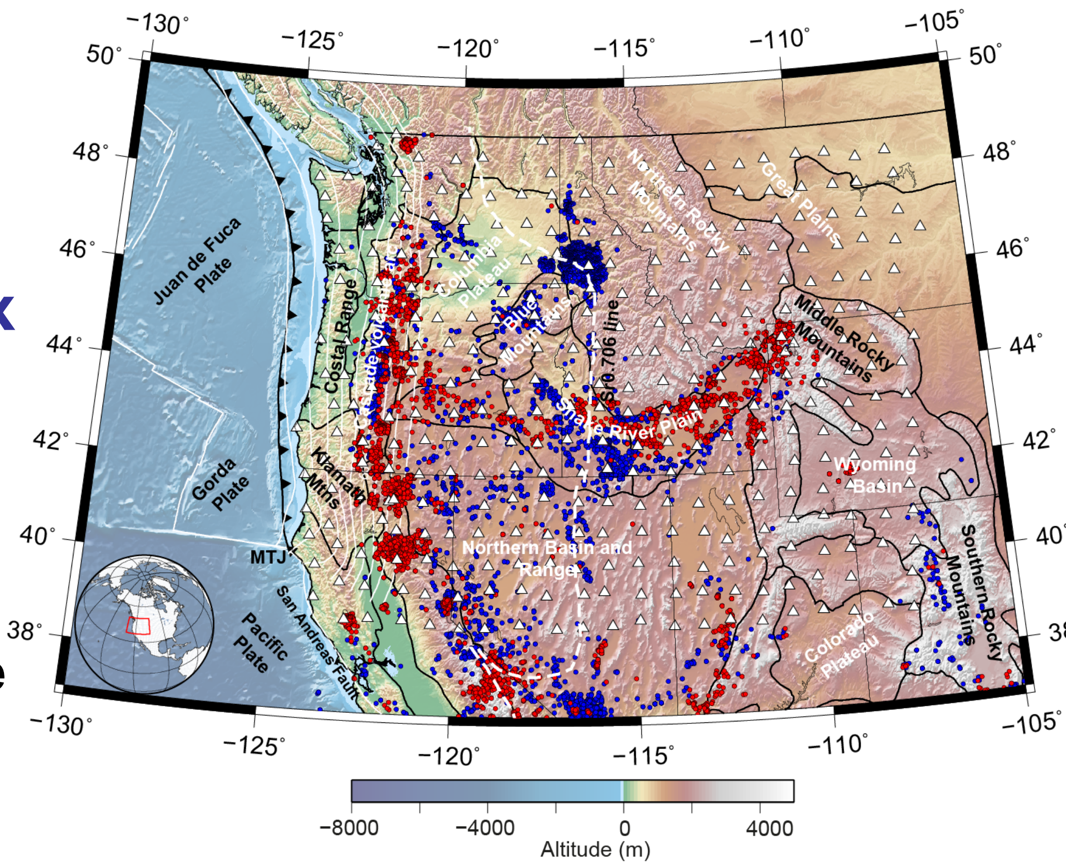


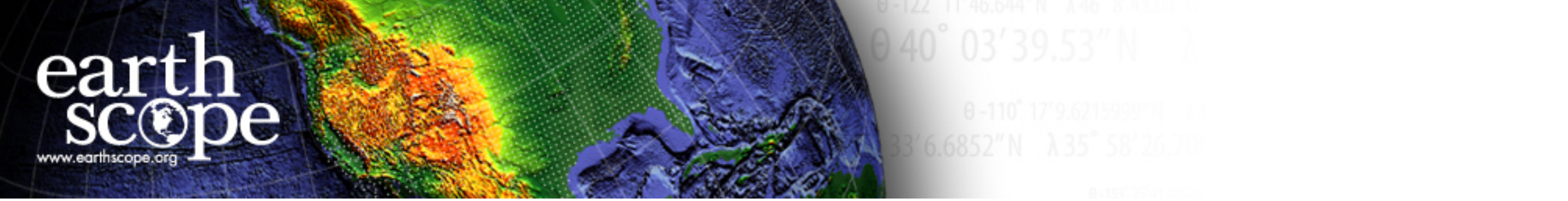
MT TA data from 2006-20011

- 325 stations
- ~70 km site spacing
- T = 10-20,000s

Spans an area of complex and varied geology:

- Subduction zone and arc
- Extensive magmatism
- Extensional Basin and Range
- Stable cratonic interior





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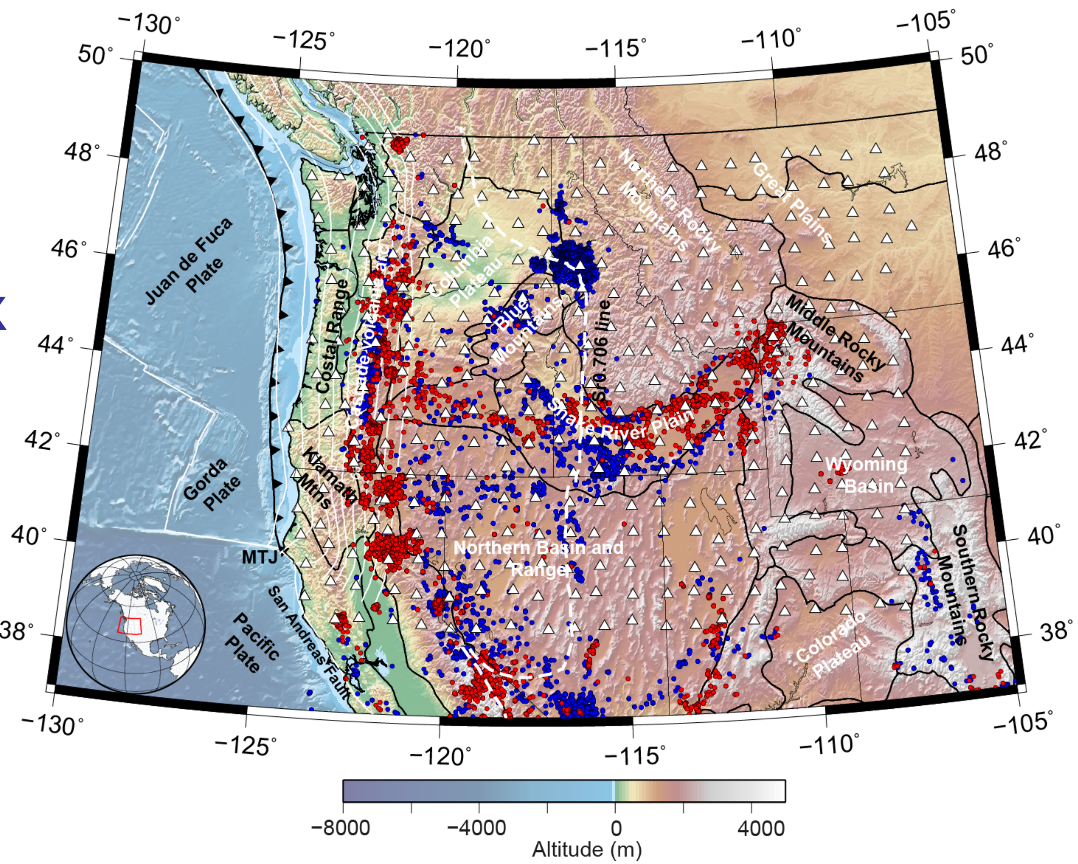
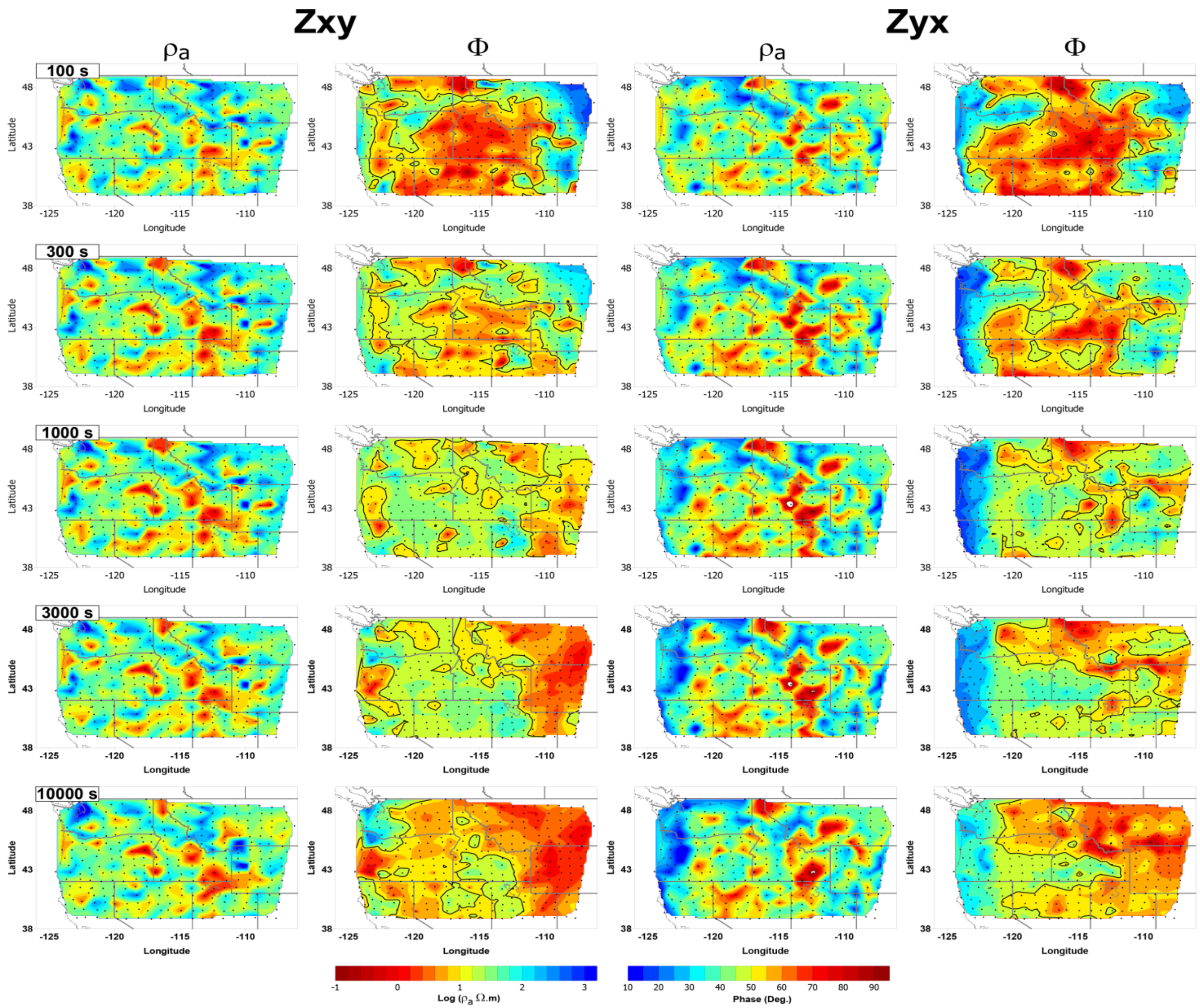


(How) is this going to work?

Interpolated maps of apparent resistivity and phase



A dataset that demands 3D interpretation

3-D Inversion of MT data

→Just becoming practical

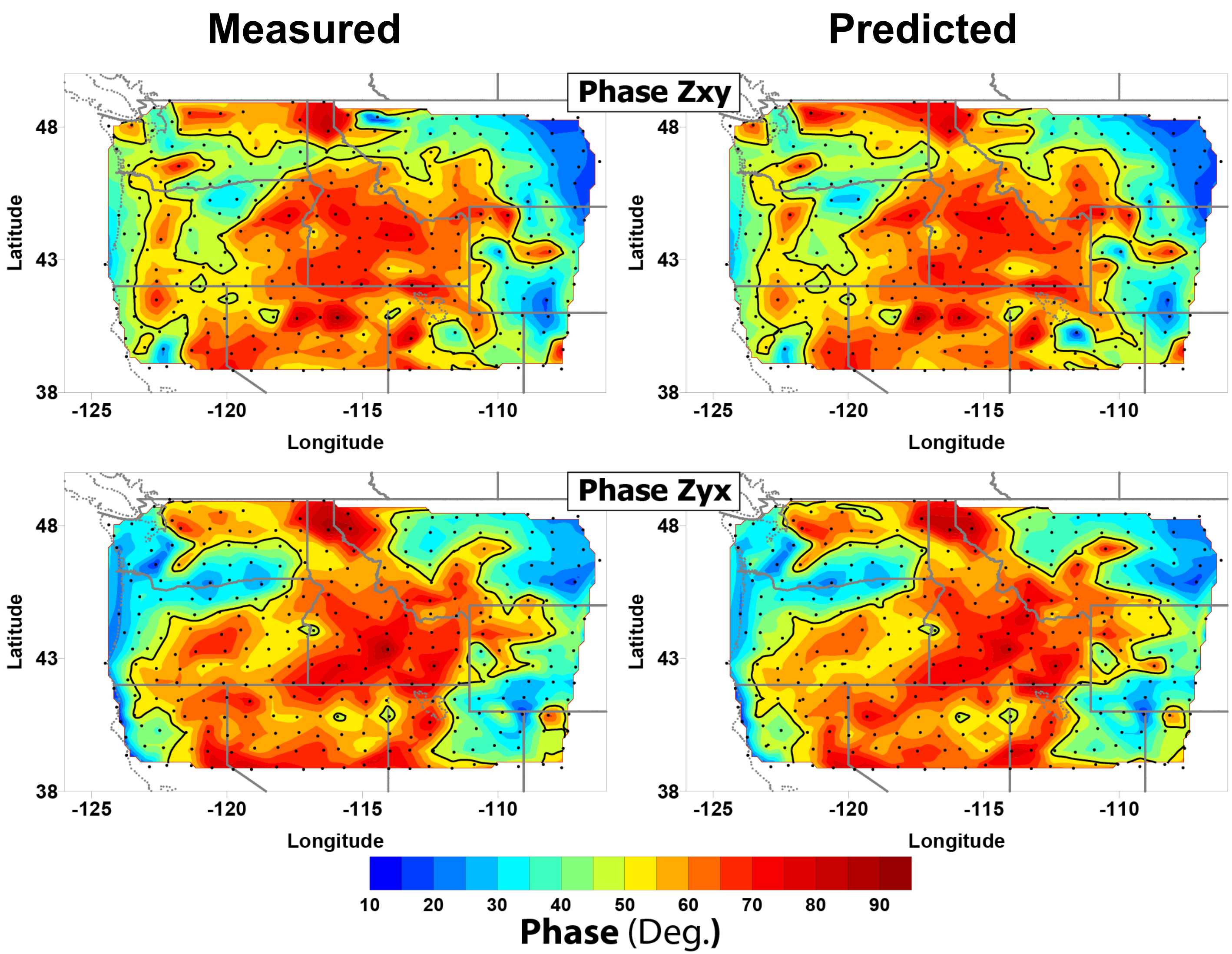
→ Still have much to learn …

- Inversion Code: Parallelized version of ModEM (Egbert and Kelbert, 2012)
- Invert everything: Full impedance (Z) and vertical magnetic transfer functions (T) for 325 stations, omitting ~3% of data
- Error floors: 5% of $\left|Z_{xy}Z_{x}\right|^{1/2}$ for Z, constant 0.03 for T
- Just directly model near-surface (static distortion) effects
- Many (> 20) inversion runs with different grids, prior models, regularization + limited resolution/hypothesis testing

Data Fit (phases at T=100 s)

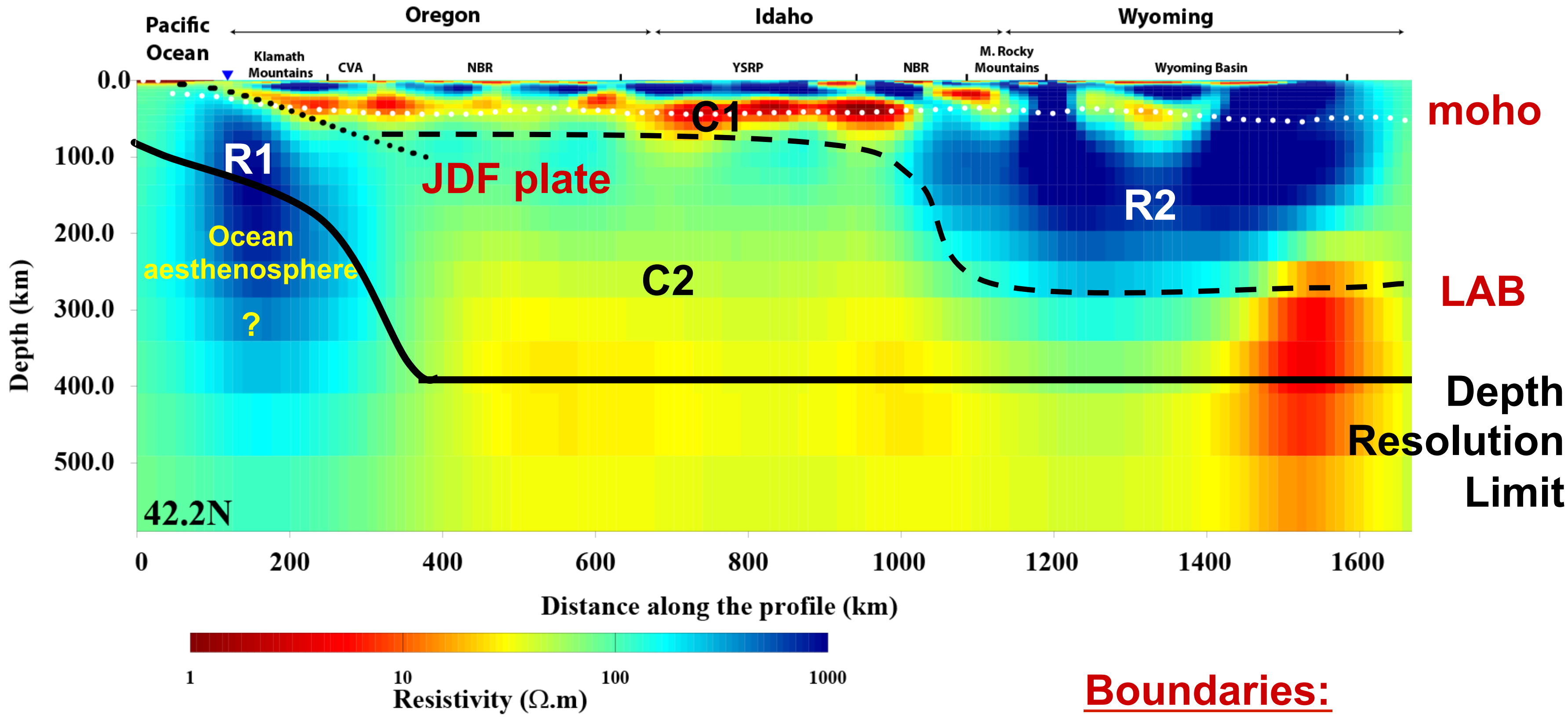
N-S Electric Currents

E-W Electric Currents



high phase→ conductivity increasing (near penetration depth)

Representative cross-section from preferred 3-D conductivity model



C1 : conductive layer near moho

C2 : aesthenospheric Mantle

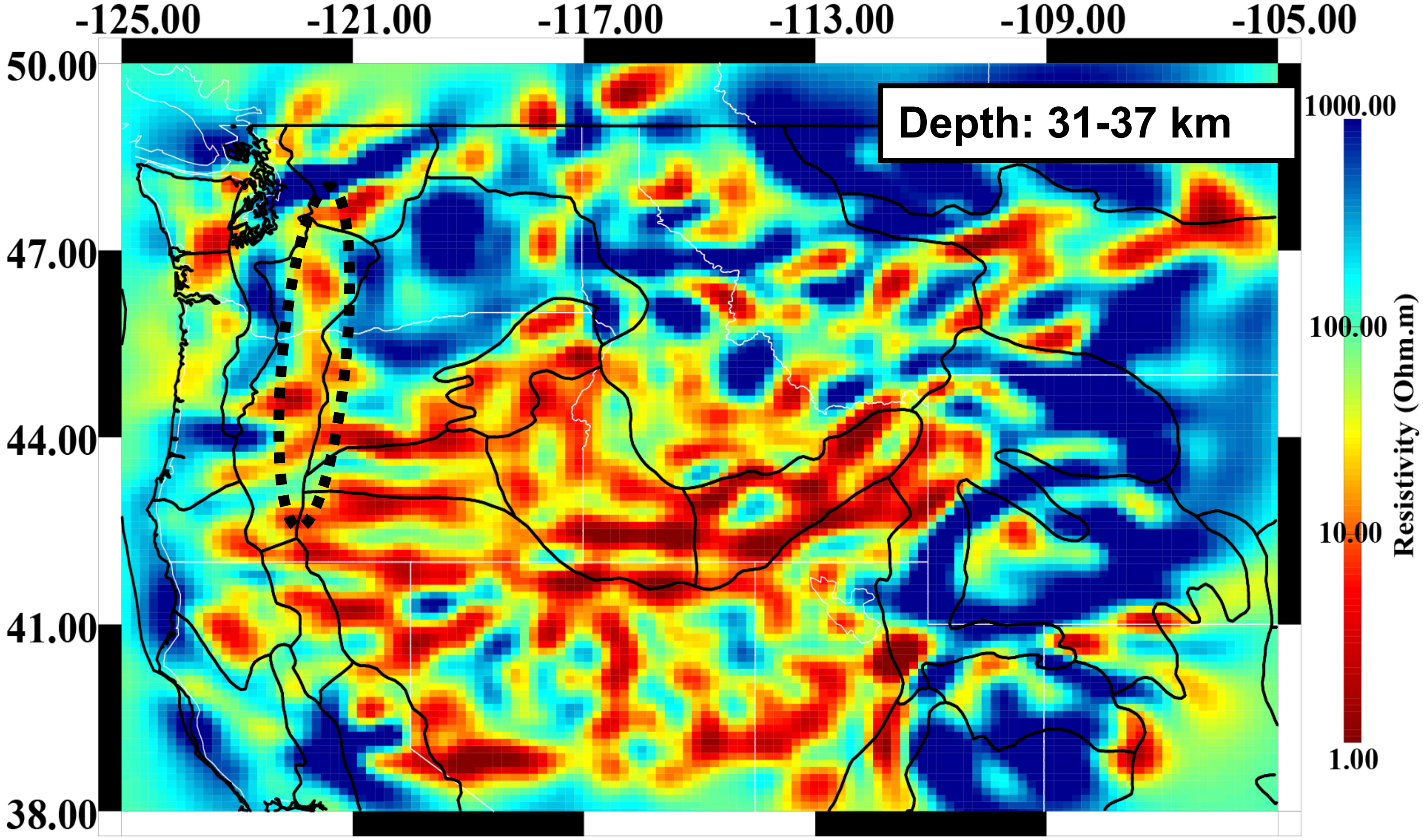
R1 : resistive oceanic lithosphere

R2 : resistive cratons

Boundaries:

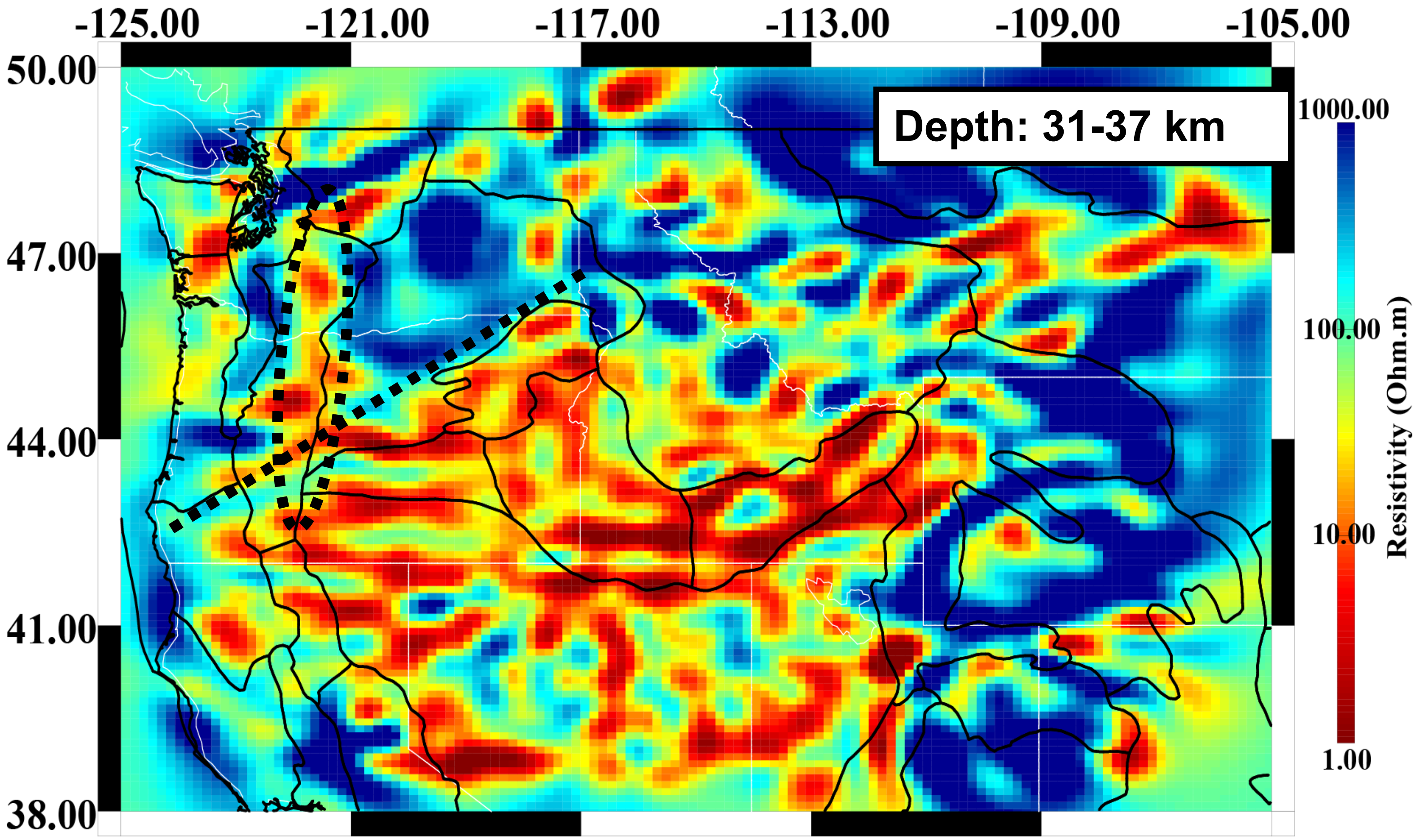
- moho: receiver functions, Alan Lavender, pers. comm.
- Top of Juan de Fuca slab: McCrory et al. (2012)
- LAB: schematic

Extensive areas of high conductivity near the moho



Cascade
Volcanic Arc

Extensive areas of high conductivity near the moho

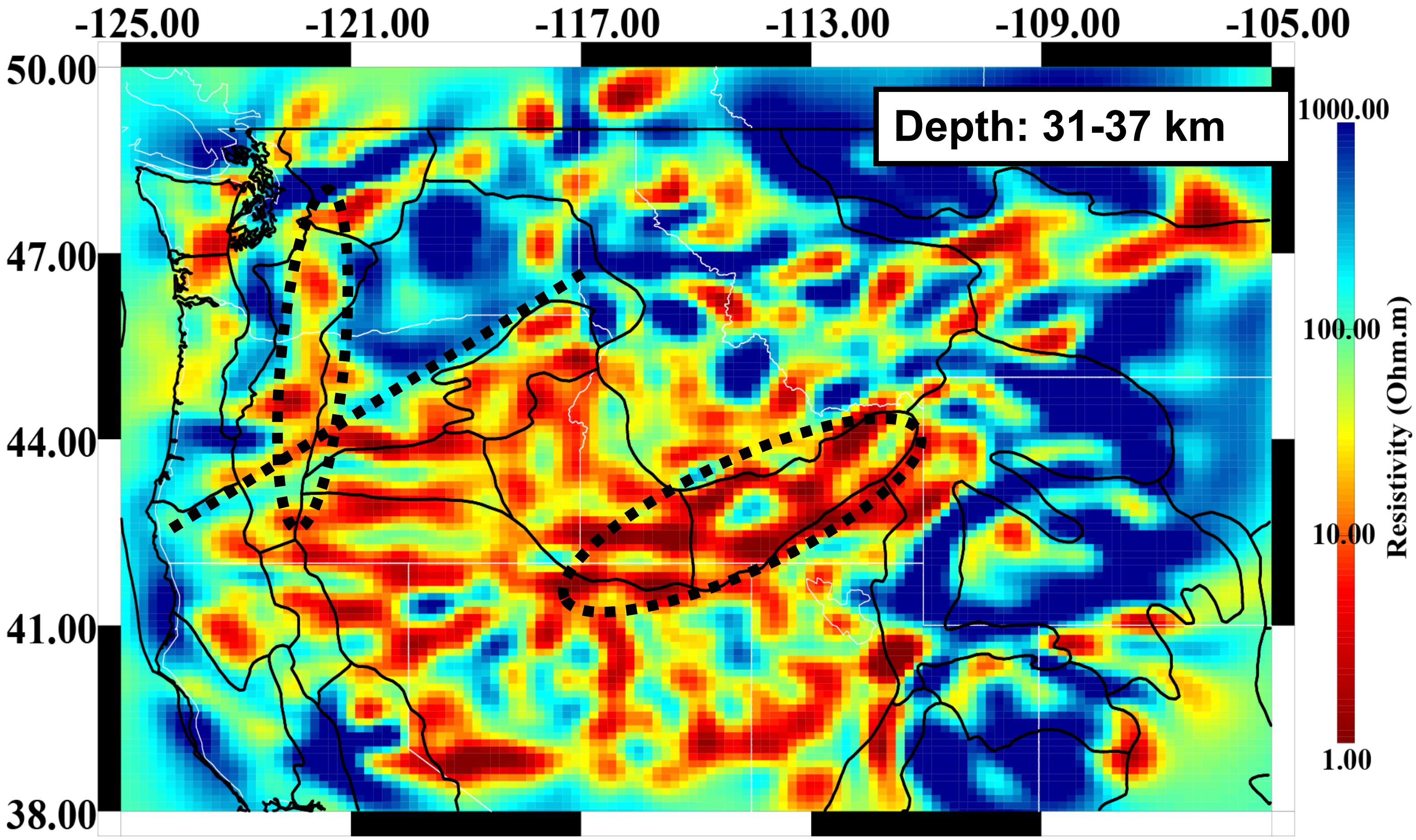


Cascade Volcanic Arc

Basin and range and Snake River Plain

→ Truncated on NW by Klamath-Blue Mts Lineamant

Extensive areas of high conductivity near the moho



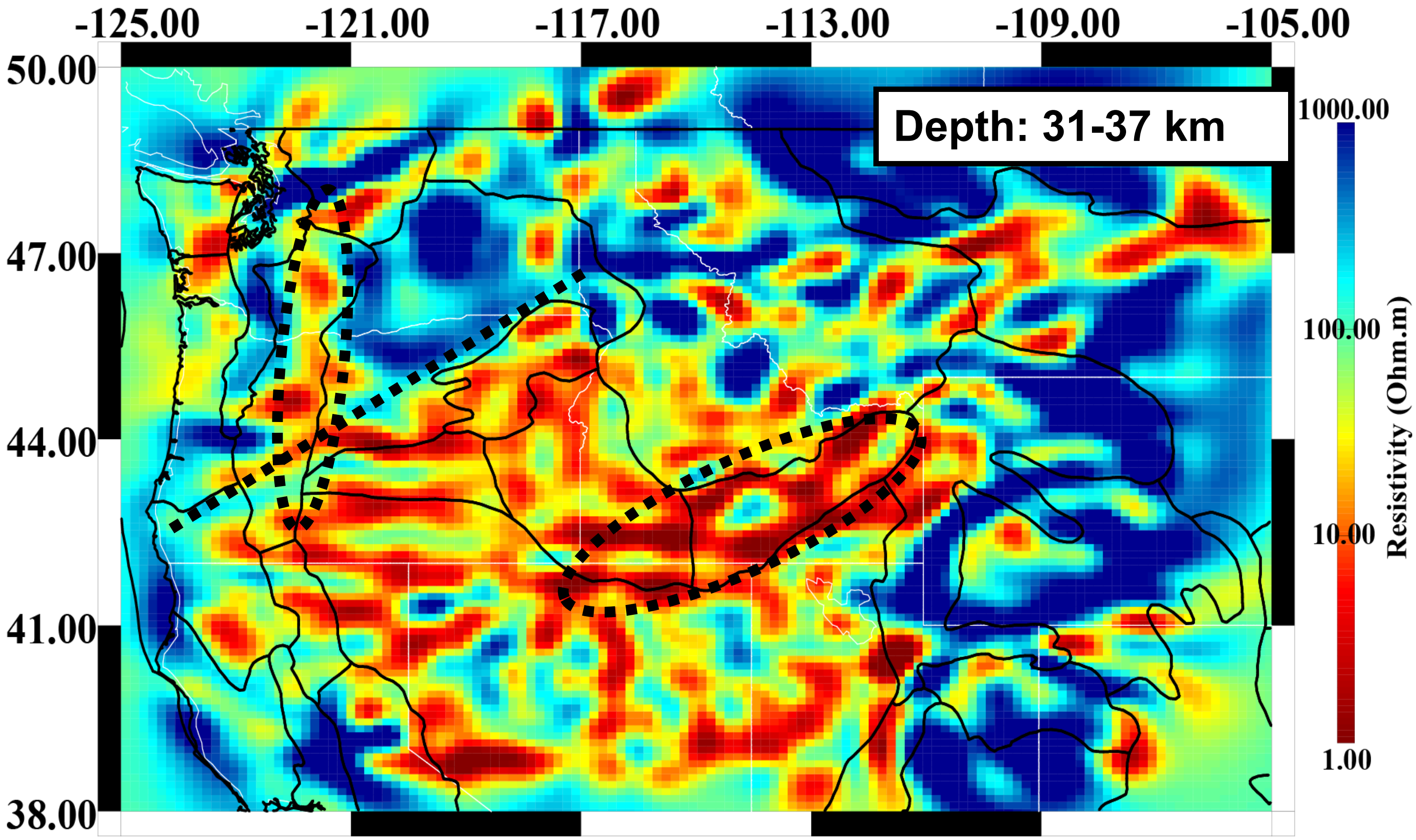
Cascade Volcanic Arc

Basin and range and Snake River Plain

→ Truncated on NW by Klamath-Blue Mts Lineamant

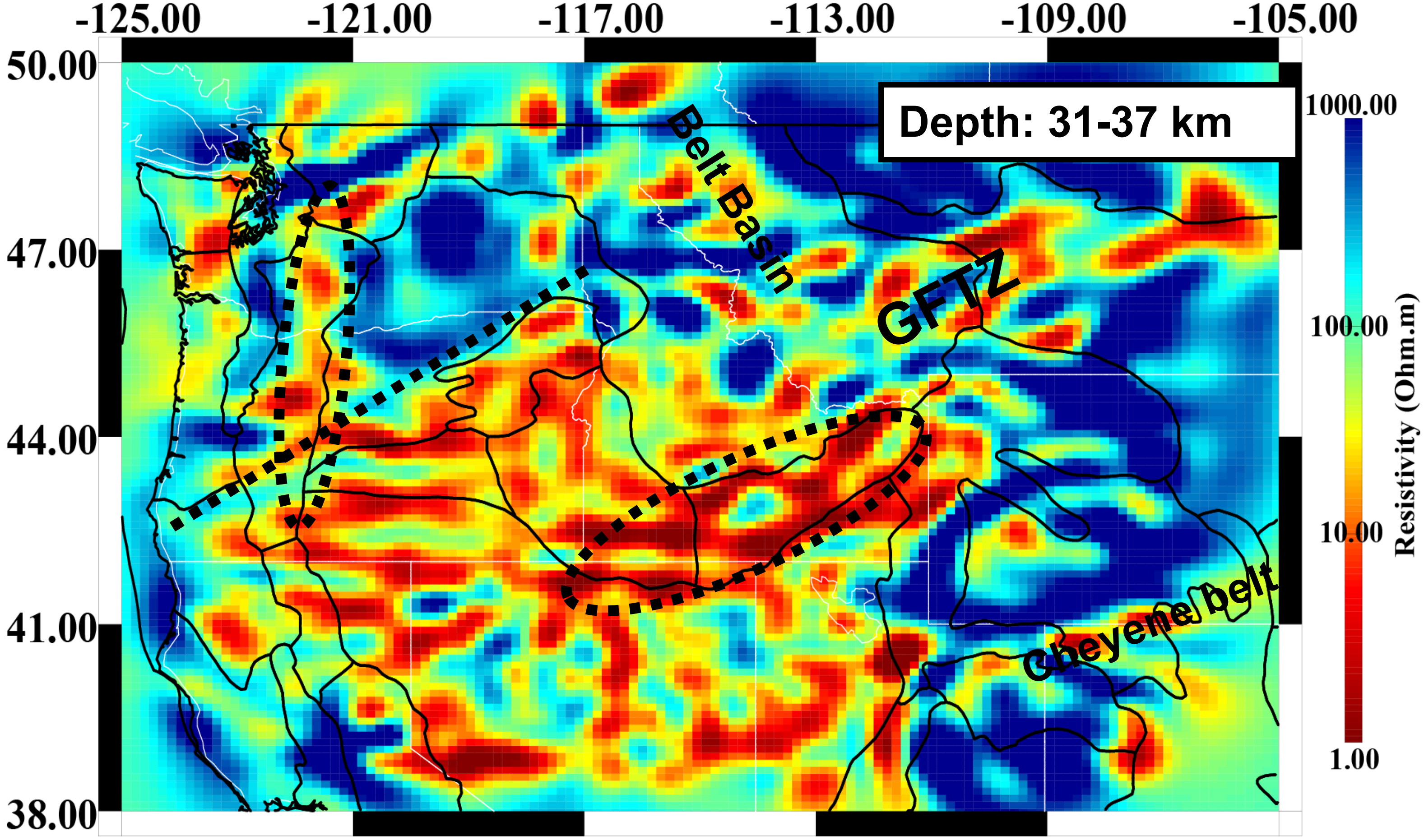
→ Highest conductivities beneath Eastern SRP

Extensive areas of high conductivity near the moho



Most plausible explanation: melt and/or magmatic/ subduction related fluids (e.g., Wannamaker et al., 1997, 2008)

Extensive areas of high conductivity near the moho



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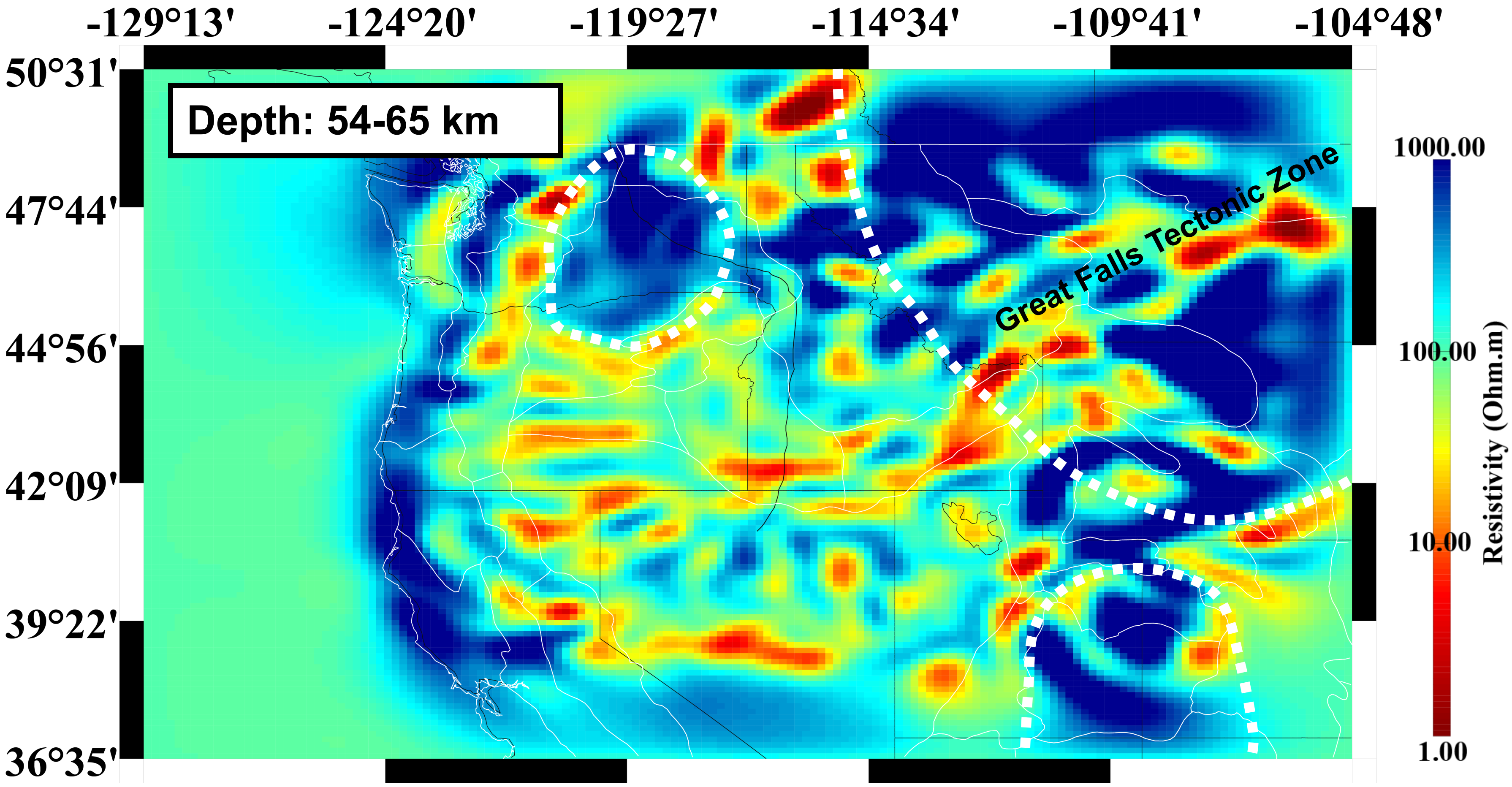
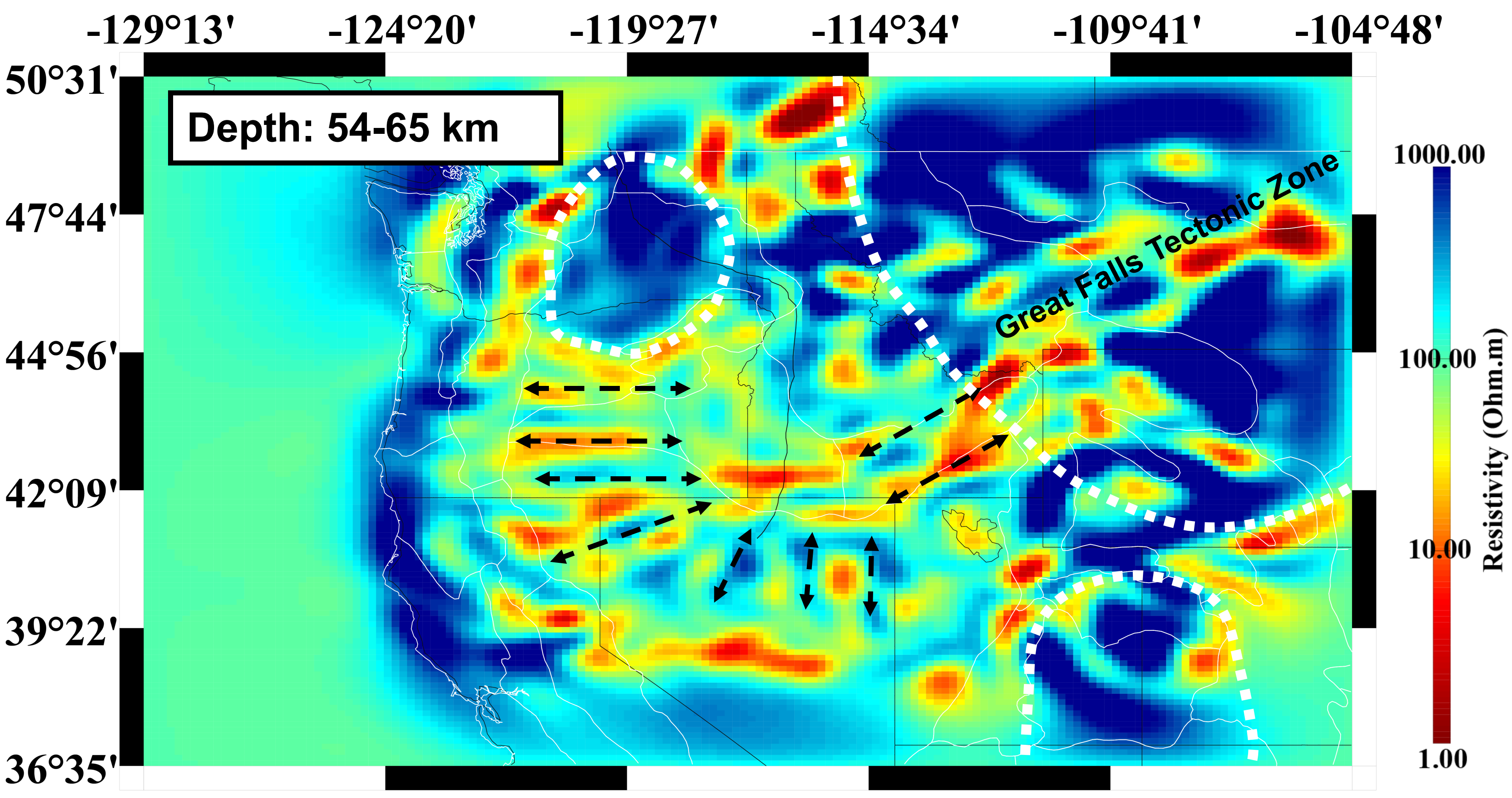
High conductivity extends into mantle

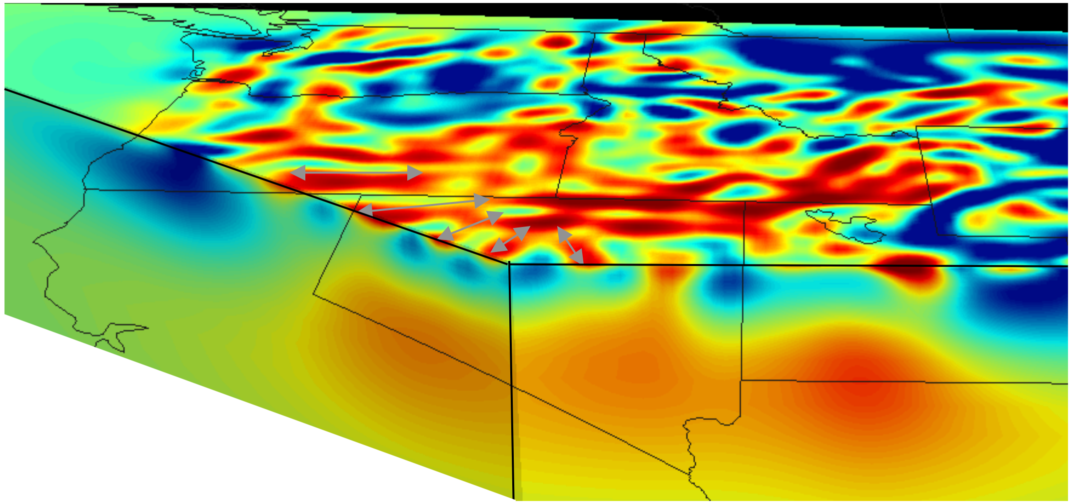


- ➢ **Resistive lithosphere beneath cratons (Medicine Hat and Wyoming) + Columbia Plateau, Colorado Plateau**

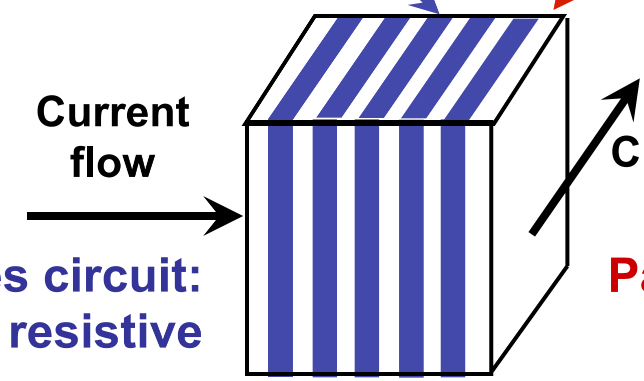
High conductivity extends into mantle



- Resistive lithosphere beneath cratons (Medicine Hat and Wyoming) + Columbia Plateau, Colorado Plateau
- Resistive and conductive stripes, widths comparable to site spacing

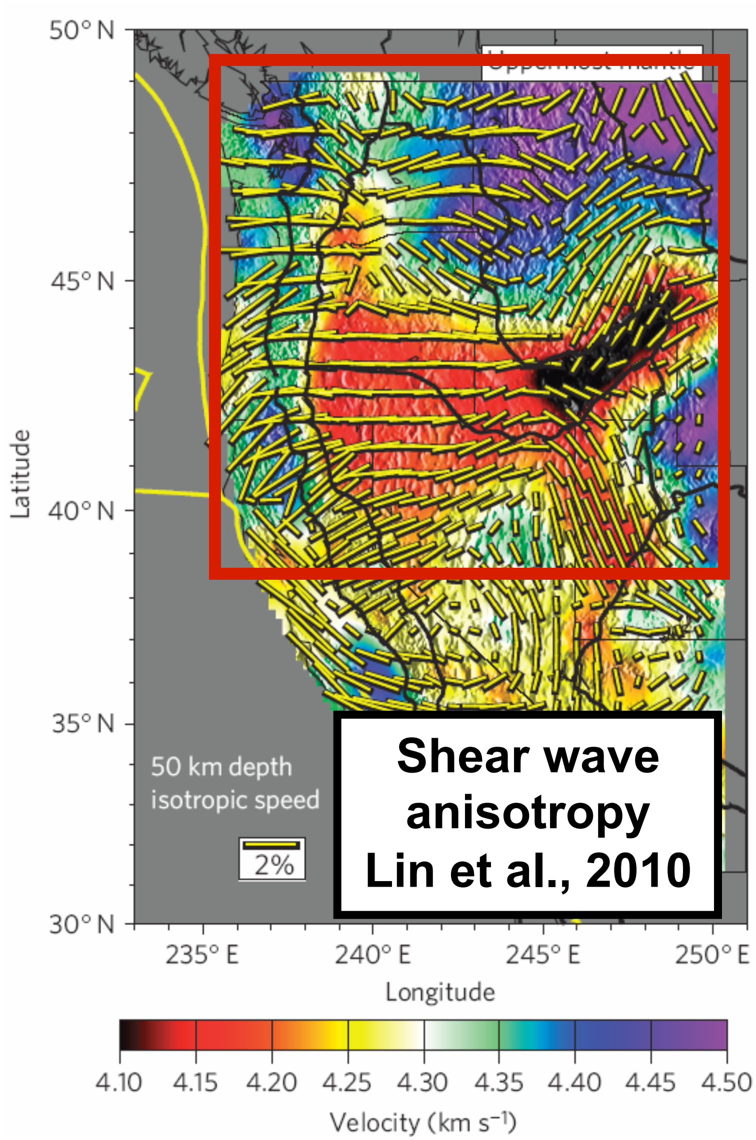


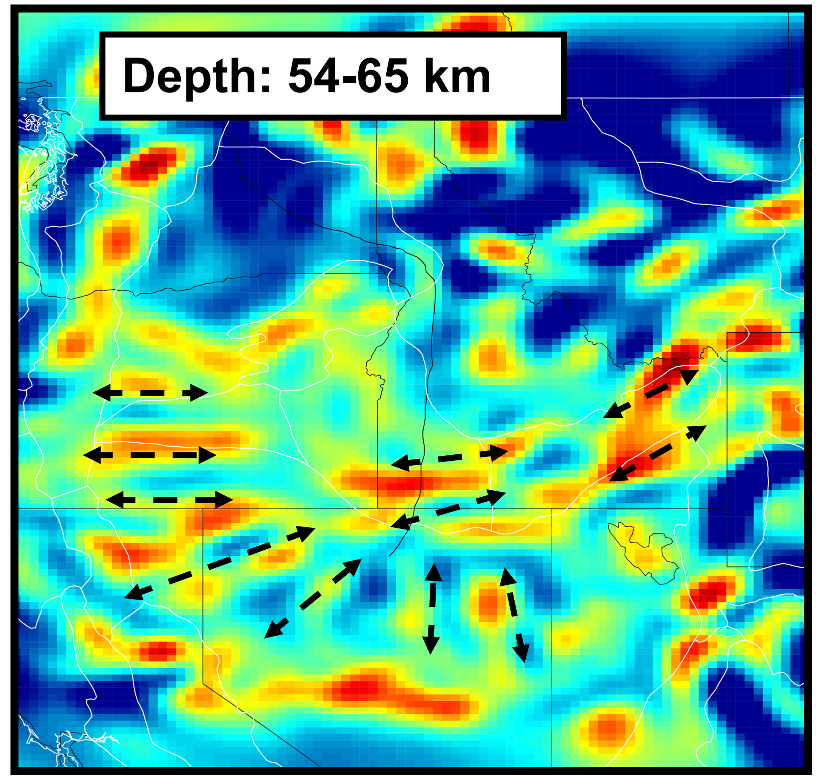
Do conductive stripes represent finer scale anisotropy?



MT data (70 km spacing) can't distinguish scale of anisotropy

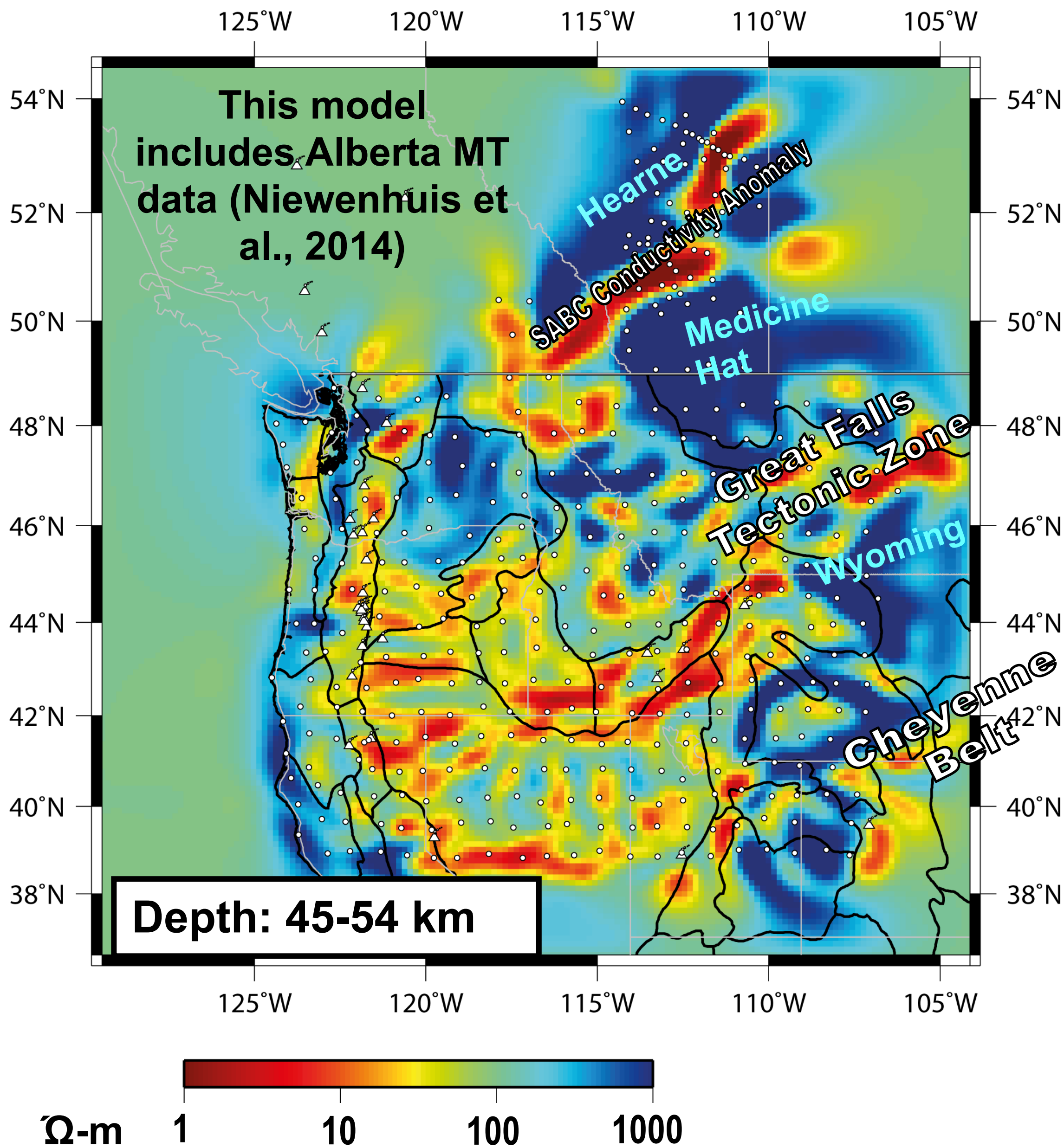
Direction of maximum conductivity matches fast axis of seismic anisotropy

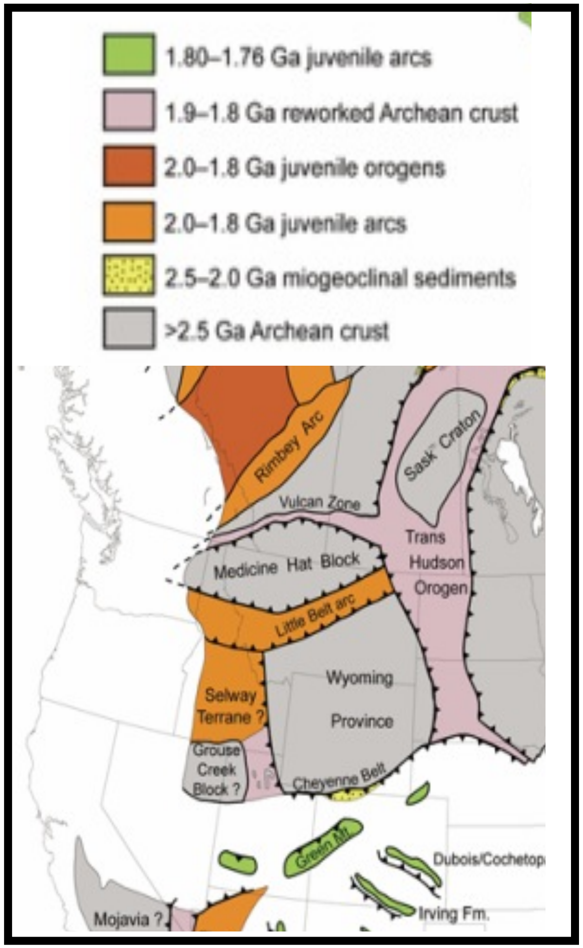




conductive anisotropy probably cannot be explained by LPO (Poe et al, 2010: relatively weak effect of water on conductivity; highest conductivities for 010 axis)

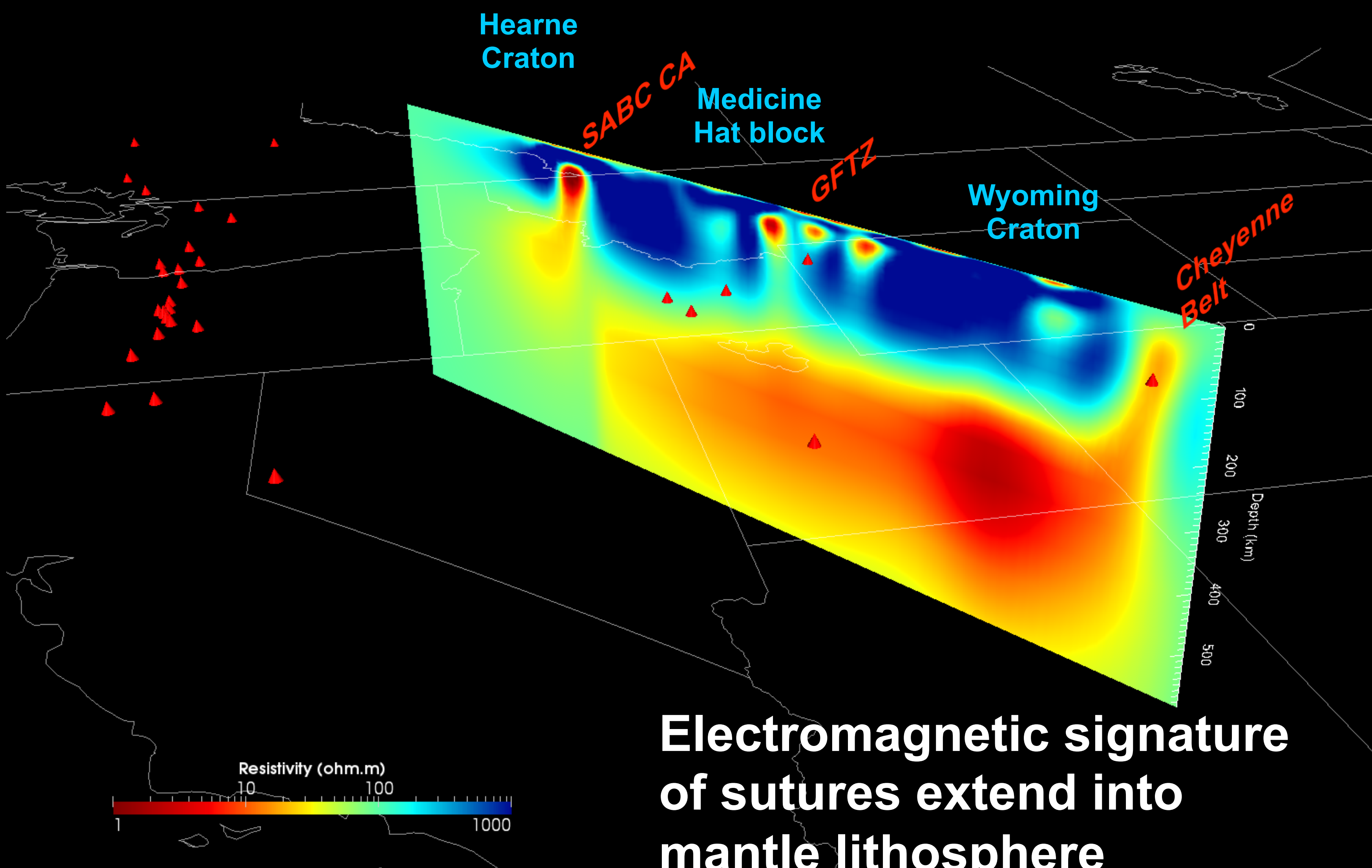
Archean Cratons and Proterozoic sutures





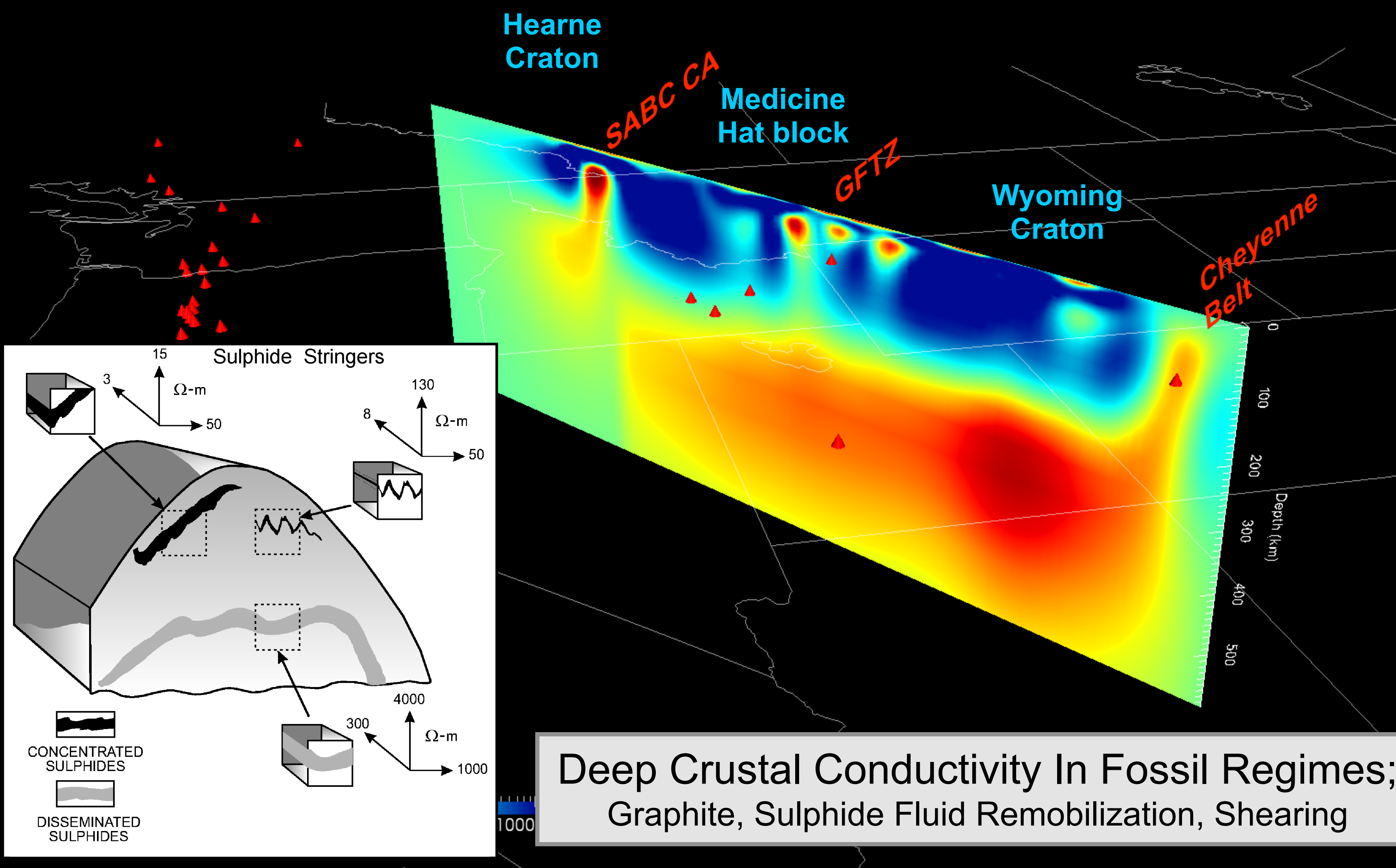
after Whitmeyer and Karlstrom (2007)

SABC CA, GFTZ and Cheyenne Belt sutures, along with Wyoming, Medicine hat Block and Hearne cratons.



Electromagnetic signature of sutures extend into mantle lithosphere

SABC CA, GFTZ and Cheyenne Belt sutures, along with Wyoming, Medicine hat Block and Hearne cratons.

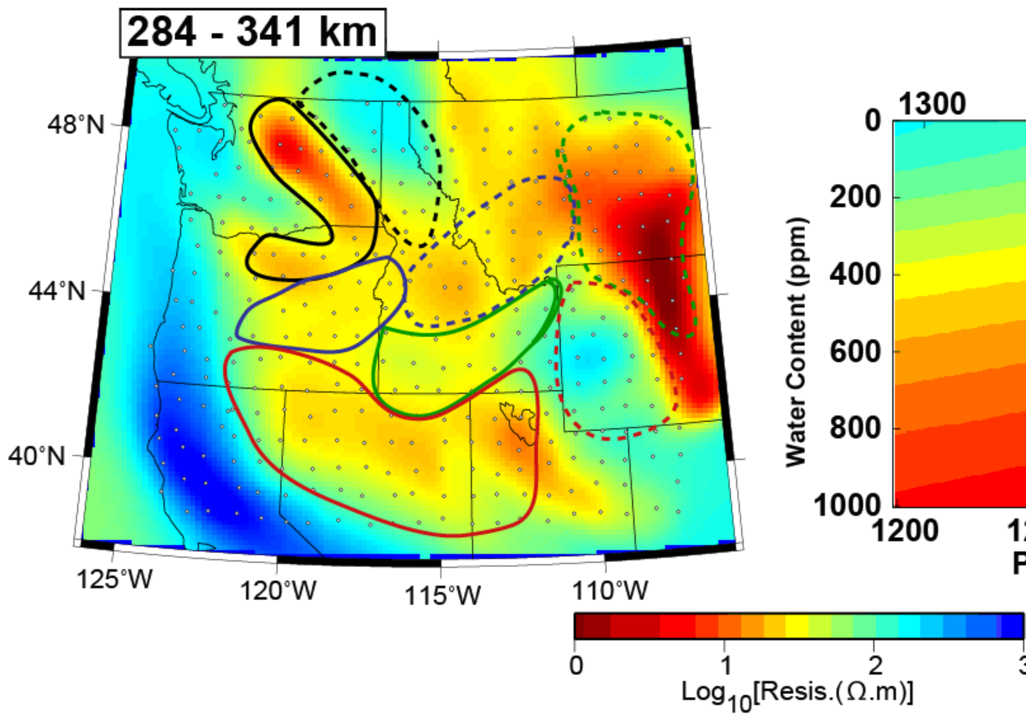


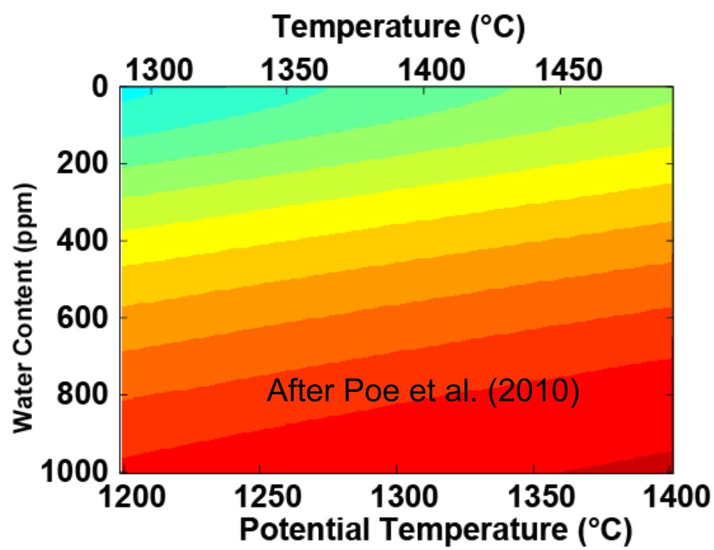
Deep Crustal Conductivity In Fossil Regimes;
Graphite, Sulphide Fluid Remobilization, Shearing

Adiabatic Geotherm and Hydrated Mantle

Divide domain into patches which are relatively homongeneous at depth

Solid – active west
Dashed– more stable interior

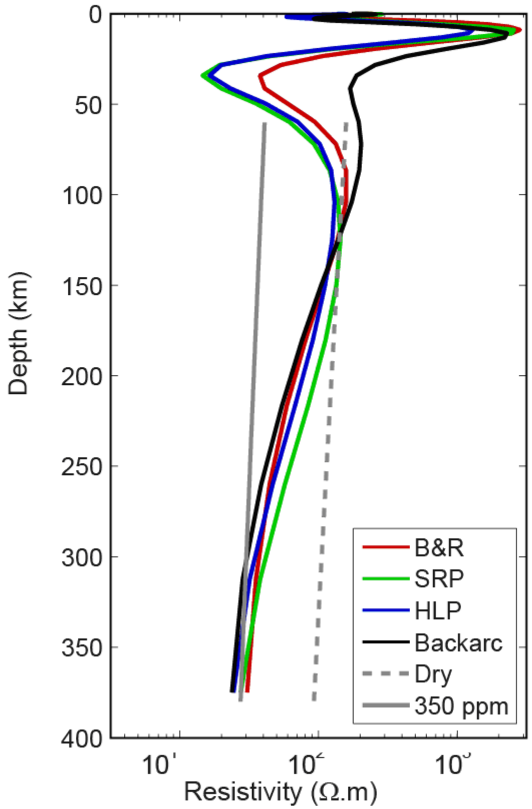




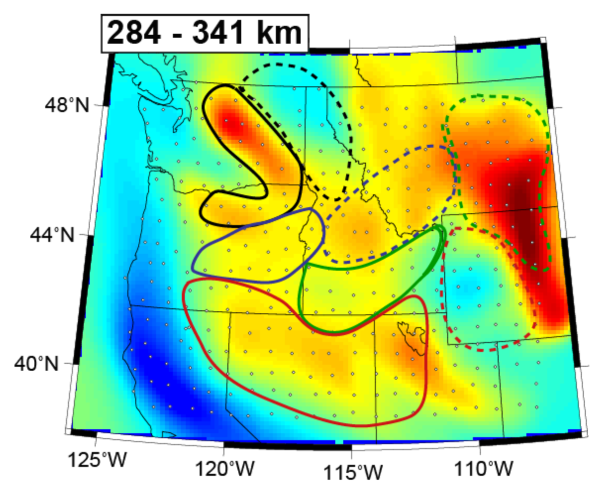
Compare average 1D resistivity profiles between regions

Adiabatic Geotherm and Hydrated Mantle

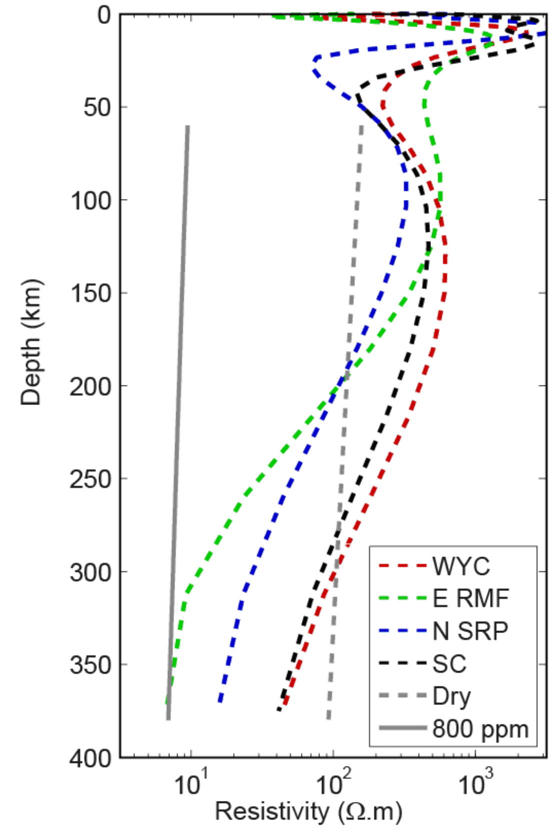
Active west



Comparison of averaged resistivity profiles to lab results (assuming adiabitic convective mantle geotherm)



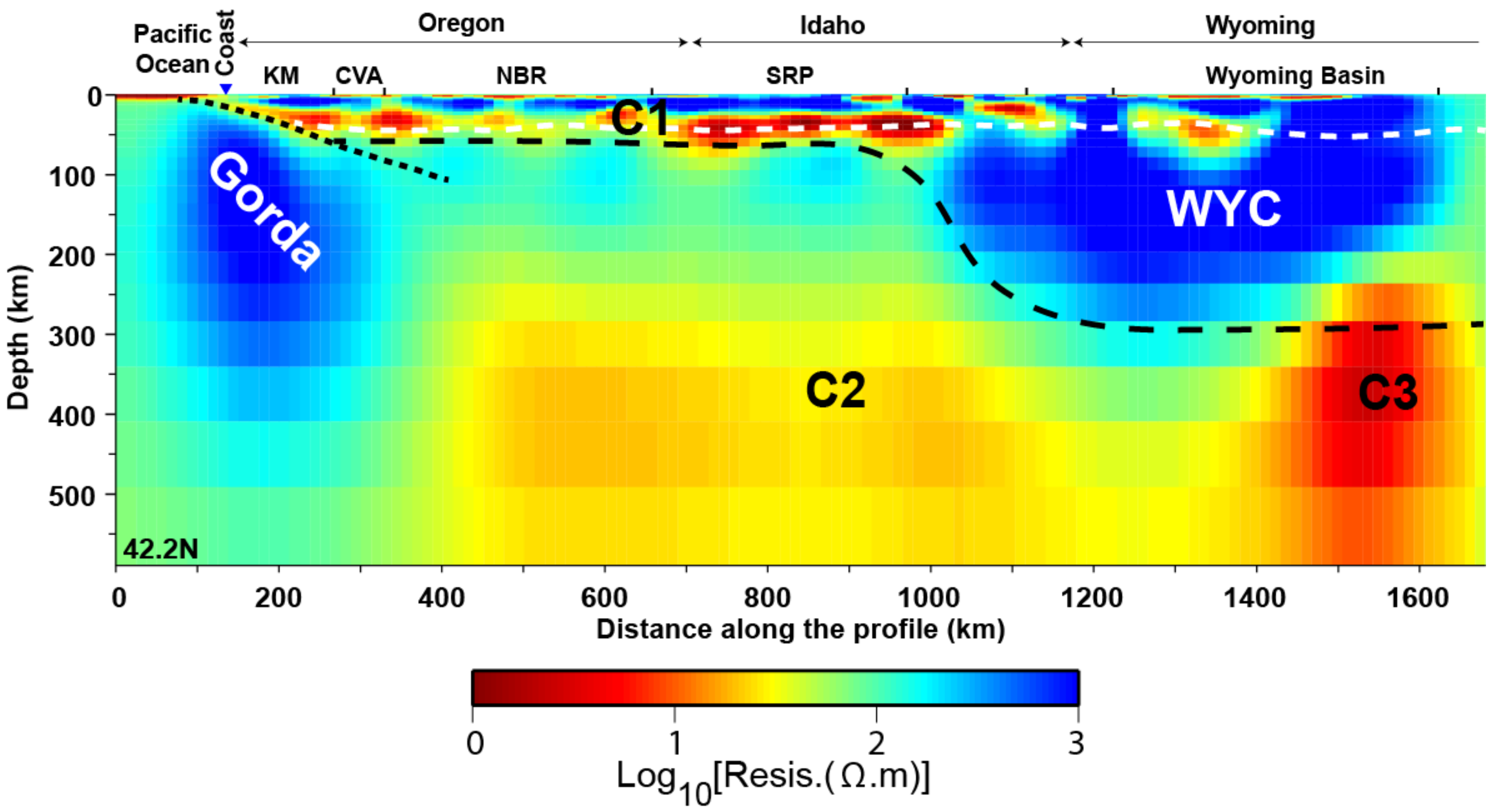
Stable interior



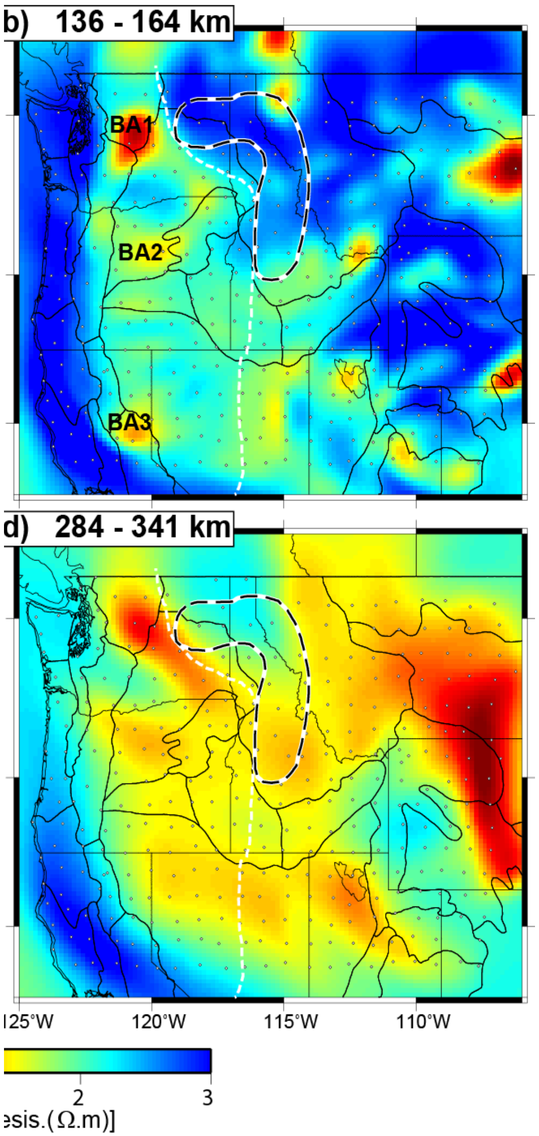
- Very thin lithospheric mantle
- Shallow aesthenosphere is dry
- Below ~250 km a few hundred ppm H_2O

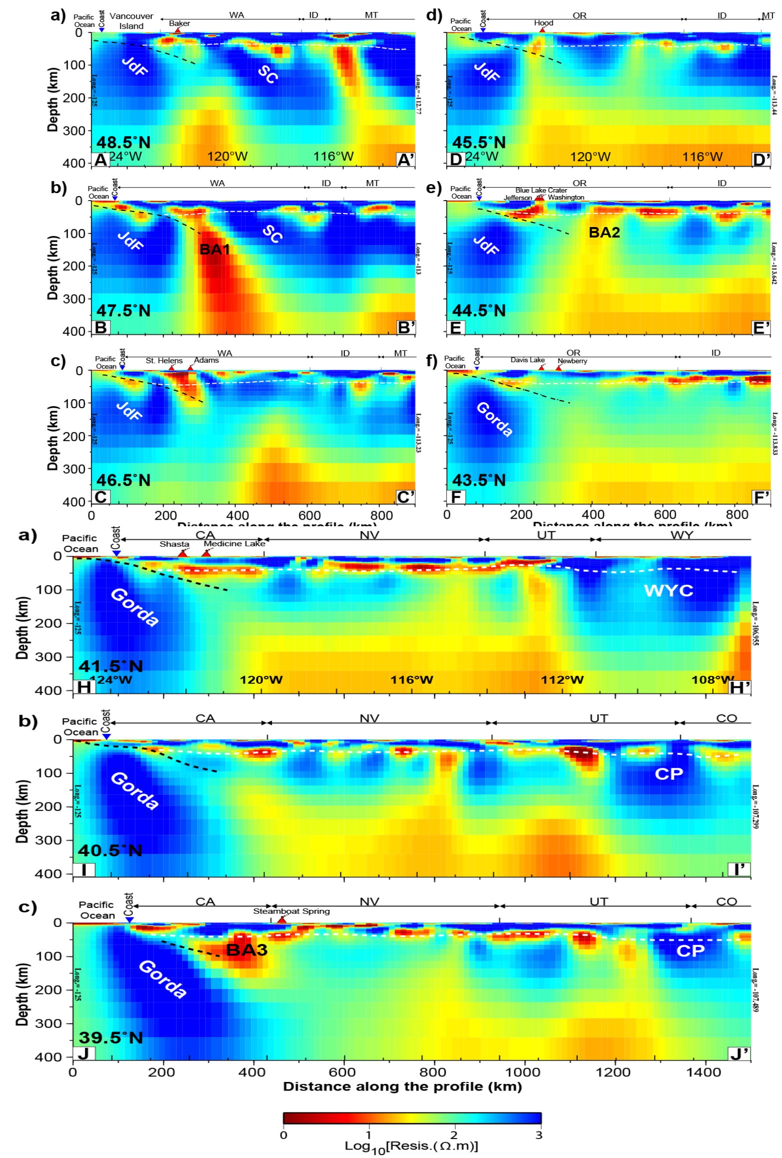
- Thick cold lithospheric mantle
  - generally hydrated aesthenosphere

Adiabatic Geotherm and Hydrated Mantle

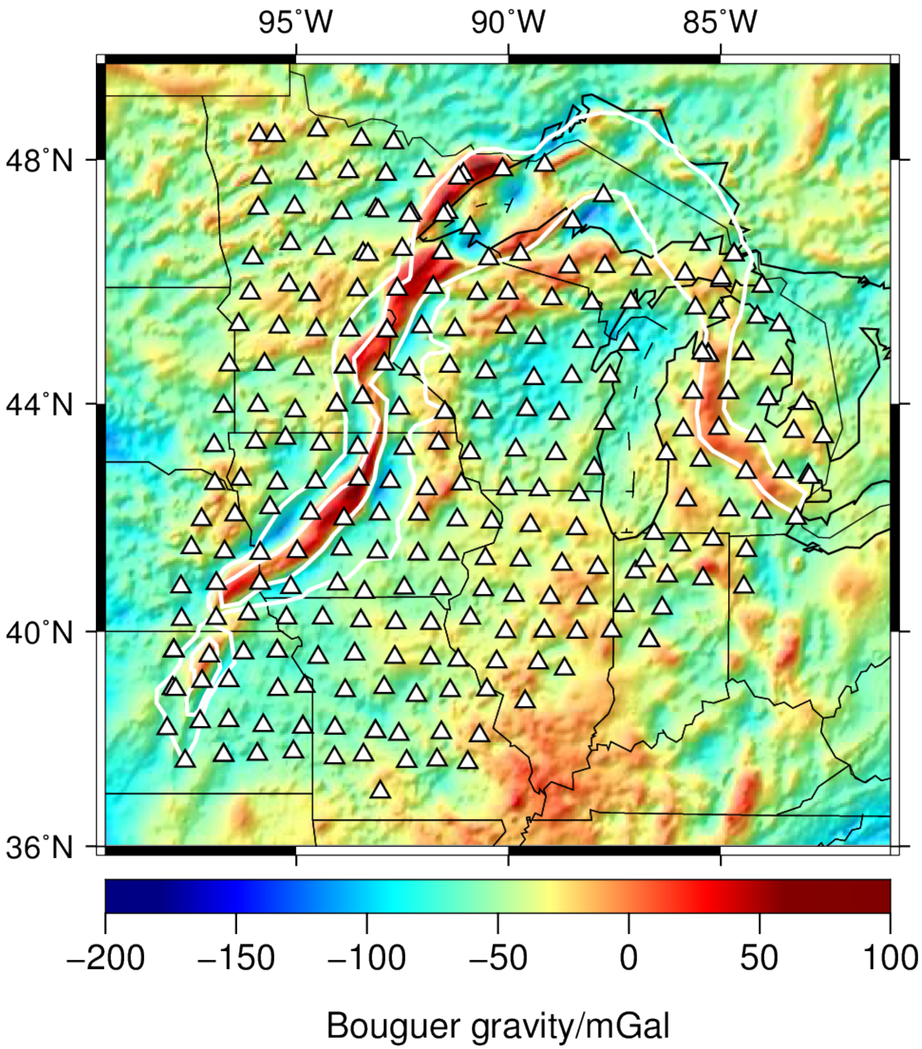


Back Arc: variable along arc … "fingers" of high conductivity… connecting into aesthenospheric high conductivty layer?





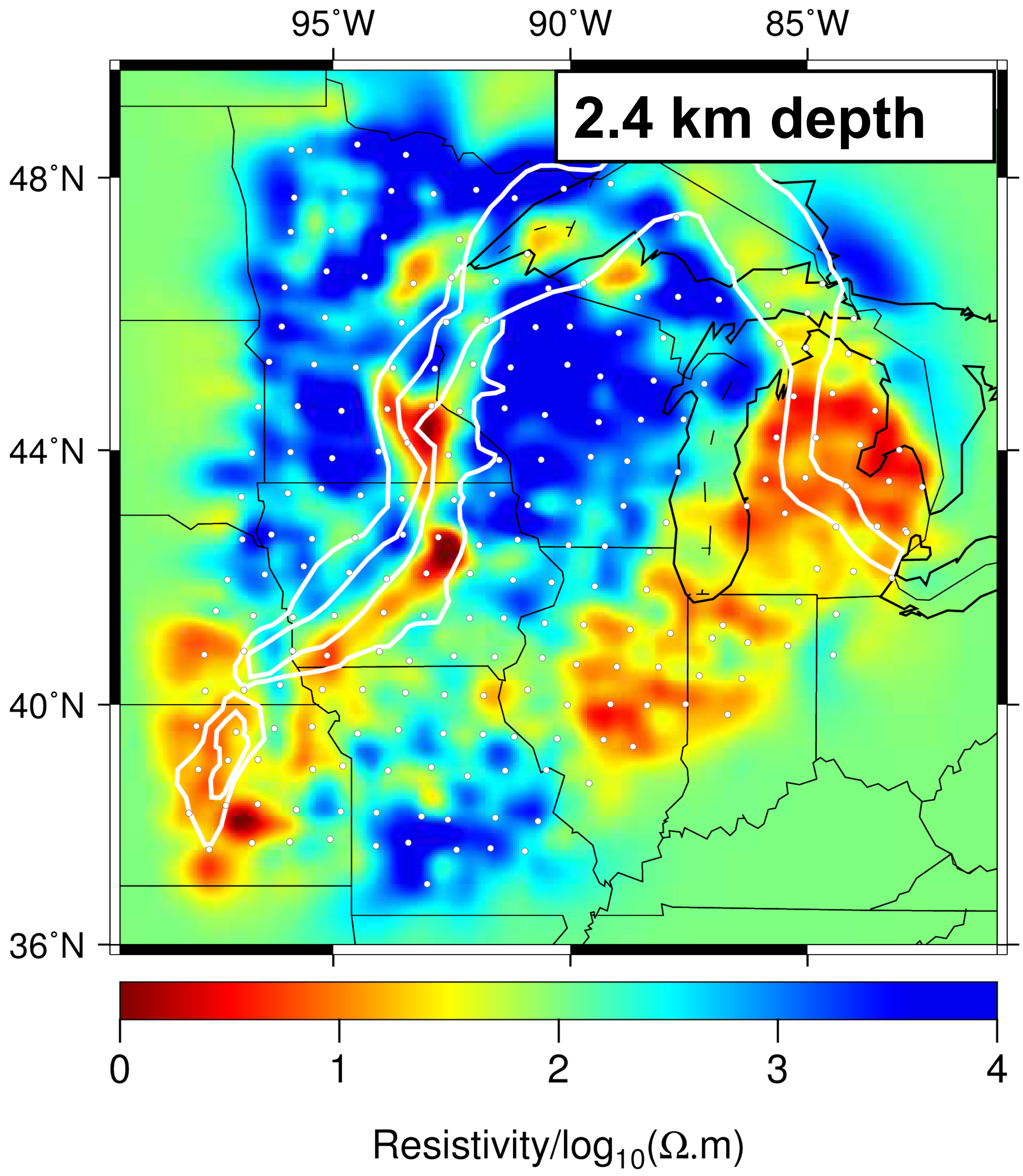
Second EarthScope MT Footprint: First Mid-Continent Rift 3D inversion results



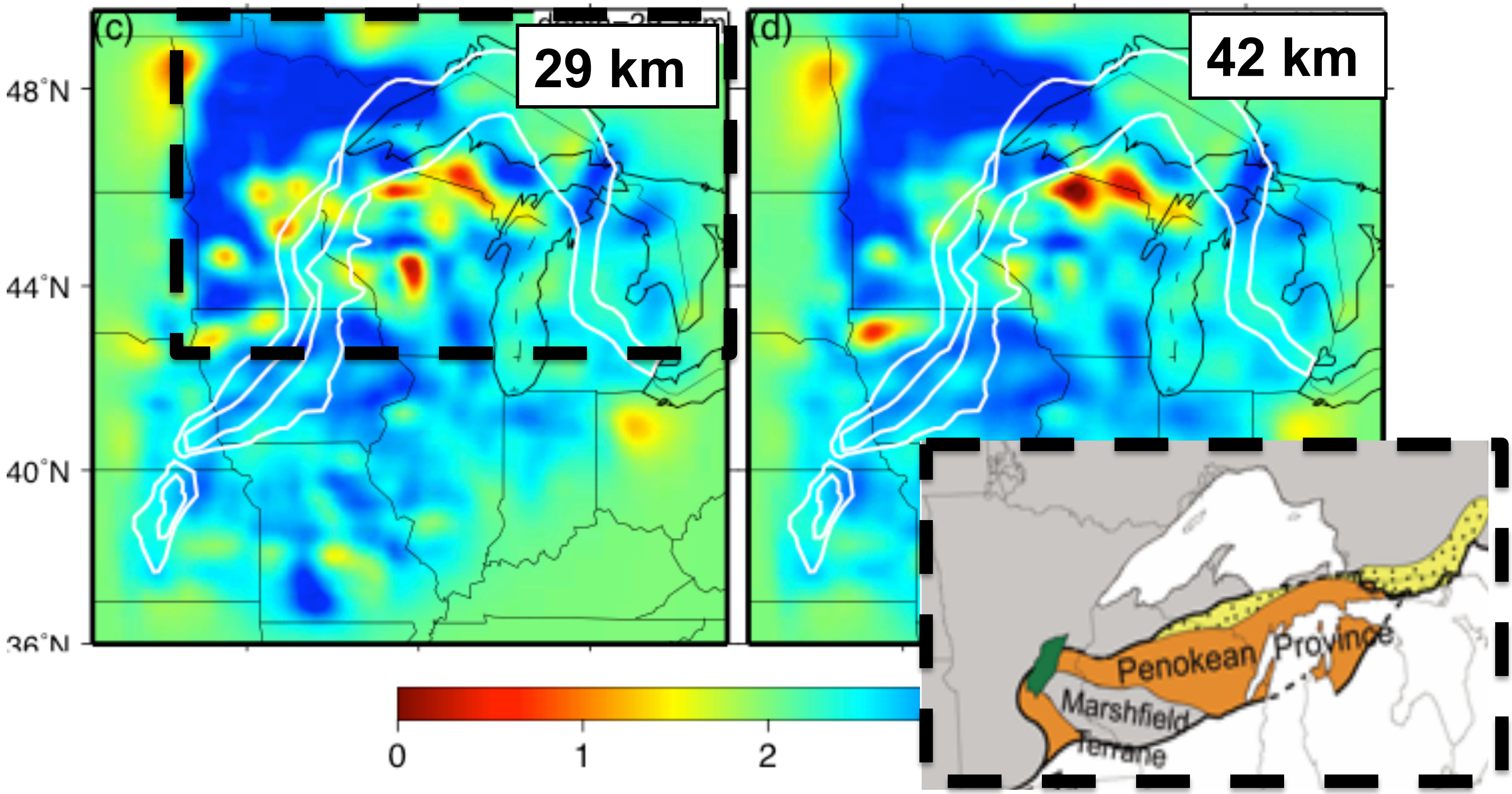
- **# of sites: 226**
- **# of periods: 26**
- **Periods range: 12 sec – 7000 sec**
- **# of iteration: 134**
- **RMS: 2.0**
- **Error floor: 5% * sqrt(|Zxy*Zyx|)**
- **Prior model: 100 Ohm.m half space**
- **Grid size: 20 km; 98 X 83 X 43**

B. Yang, G. Egbert, N. Meqbel, A. Kelbert

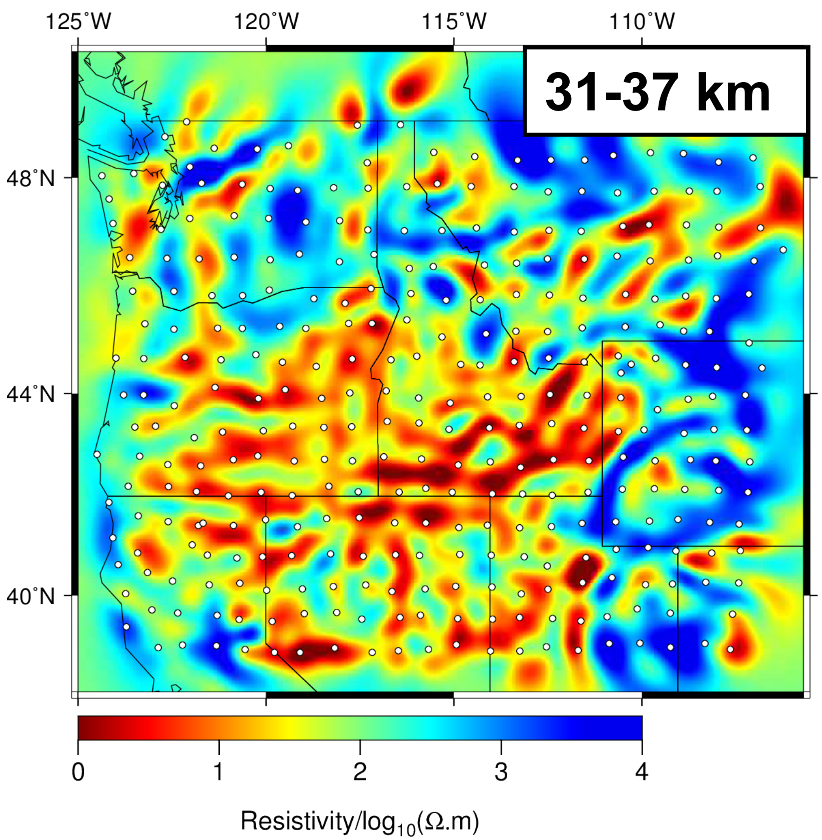
Shallow Structure: rift is clearly delinieated



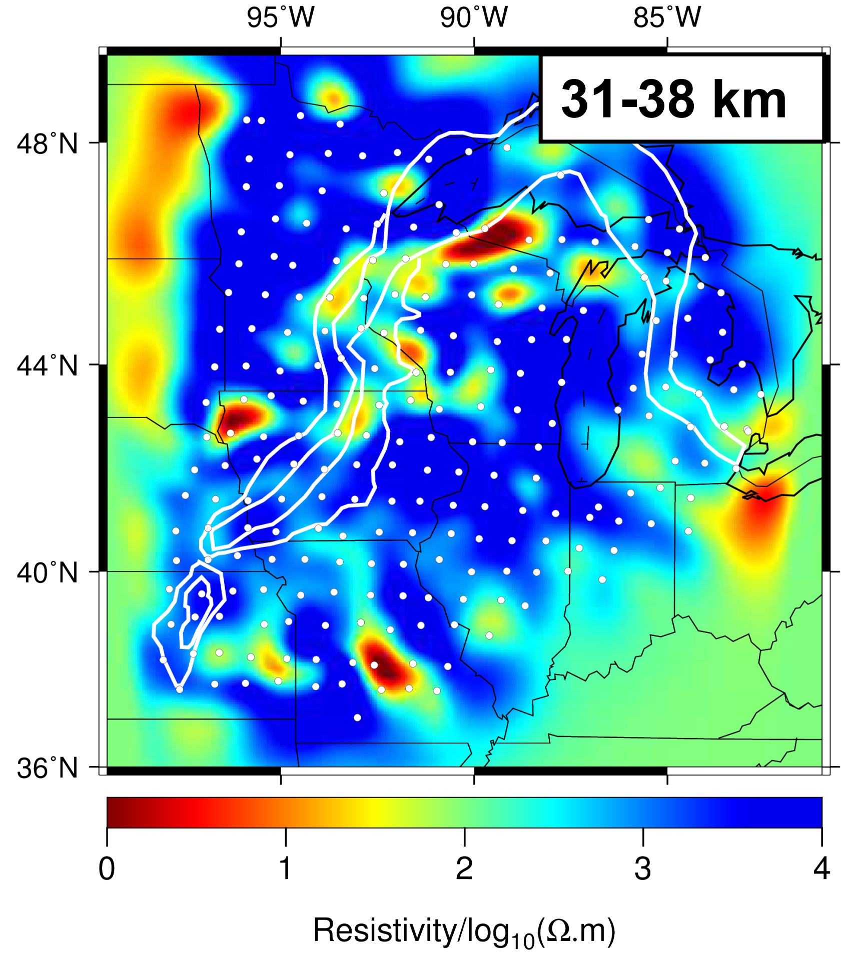
Area of patchy high conductivity in the lower crust (extending into lithospheric mantle) coincides with location of an oceanic arc accreted to the Superior craton at ~1.8-1.9 Ga



Whitemeyer and Karlstrom, 2007



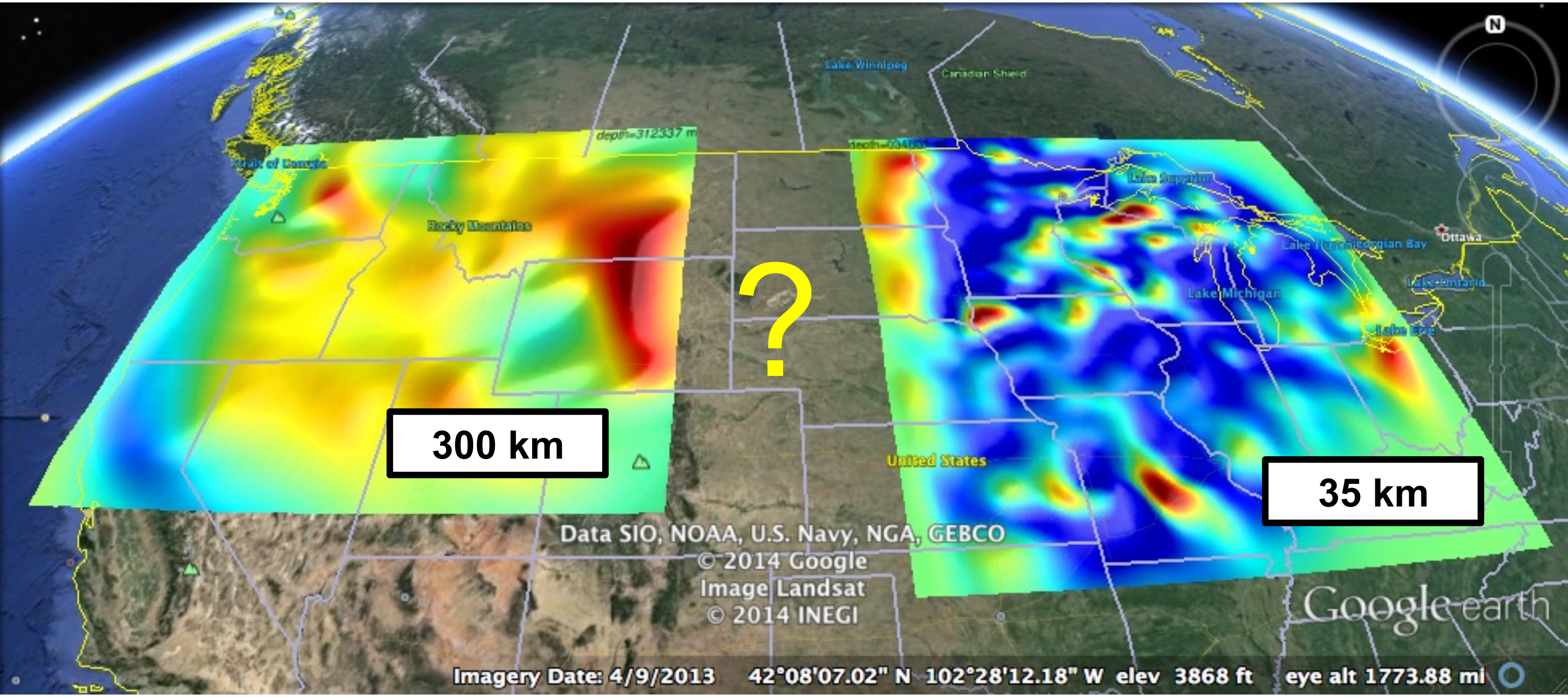
Pacific Northwest



Mid-Continent Rift

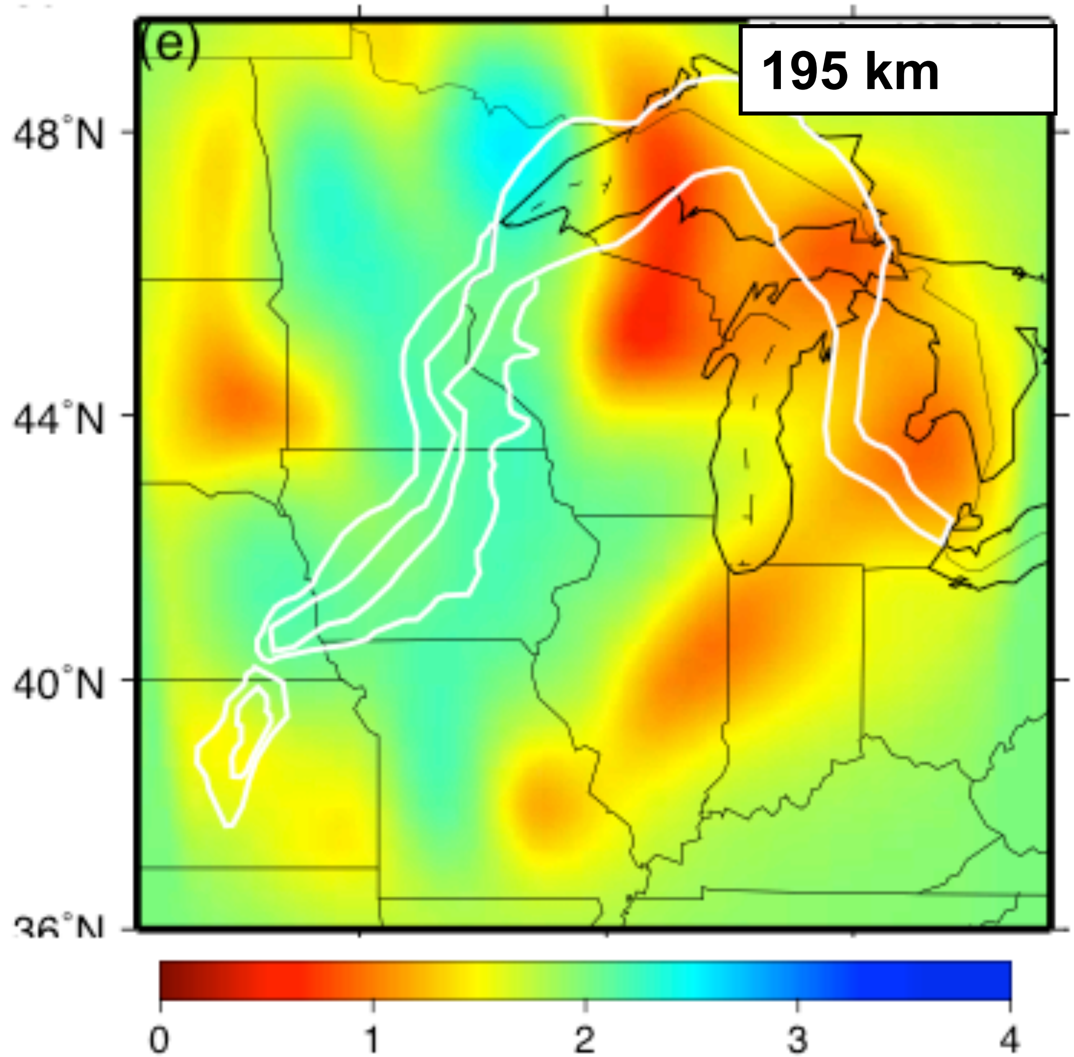
High conductivity near moho (lower crust): ubiquitous in tectonically active areas, but not stable

Possible Artifacts: Conductive Features Near Array Edges



… Full coverage of US is warranted!

Deeper resistive roots beneath western arm of MCR



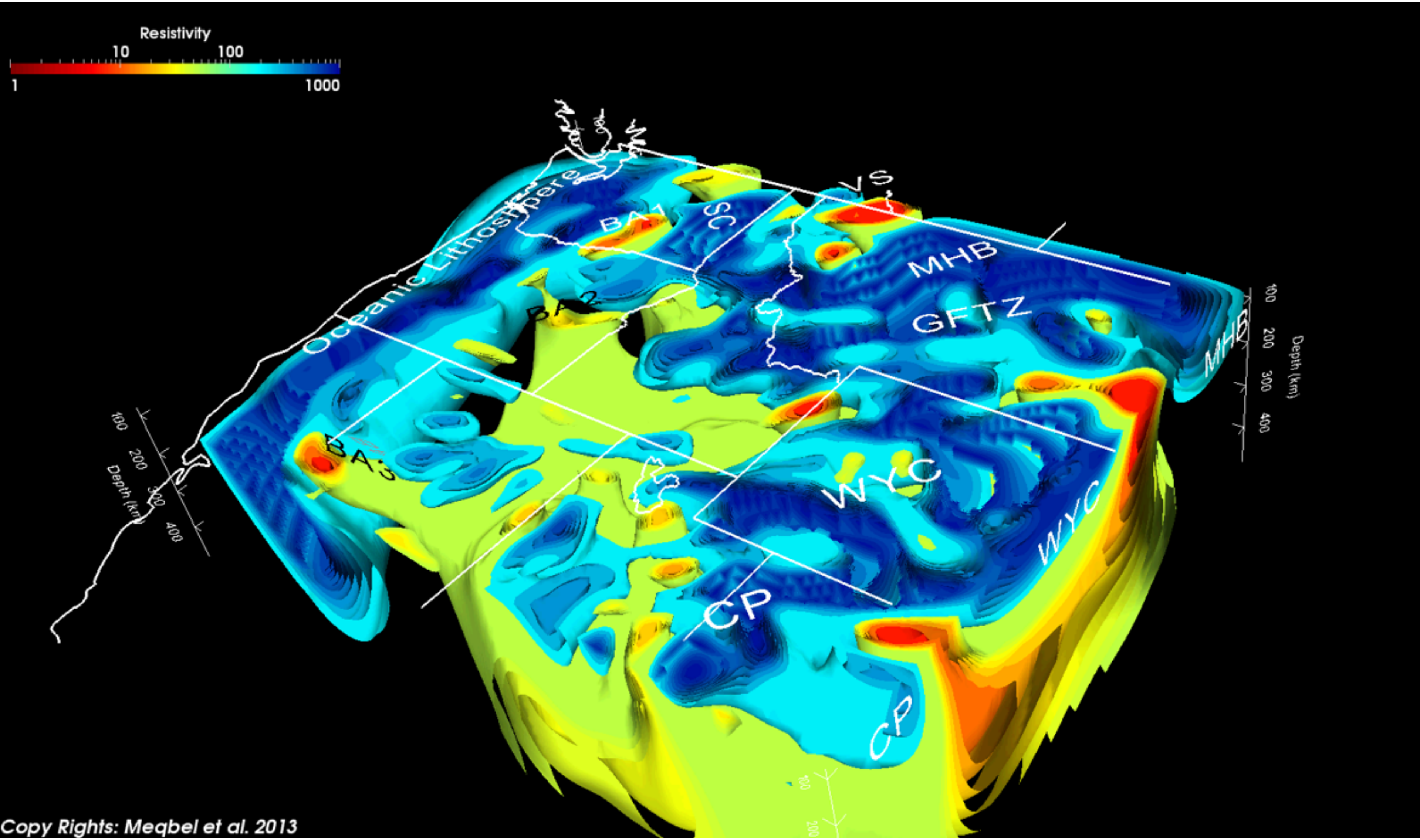
Summary

➢MT-TA array + 3D inversion approach seems to work quite well!

→broad view of high conductivity layers in the lower crust and uppermost mantle

→ large aperture allows resolution of deeper later variations in resistivity (LAB and beyond)

→ conductive sutures record continental assembly


Resistivity
10
100
1
1000
Oceanic Lithosphere
BA1
SC
VS
MHB
BA2
GFTZ
MHB
BA3
WYC
WYC
CP
CP
Depth (km)
Depth (km)
Copy Rights: Meqbel et al. 2013

EMScope: MT component of USArray

Transportable array plans (2014-2018)