# Development and Prospects of Continental-Scale Resistivity Surveying for Orogenic Processes and Resource Controls


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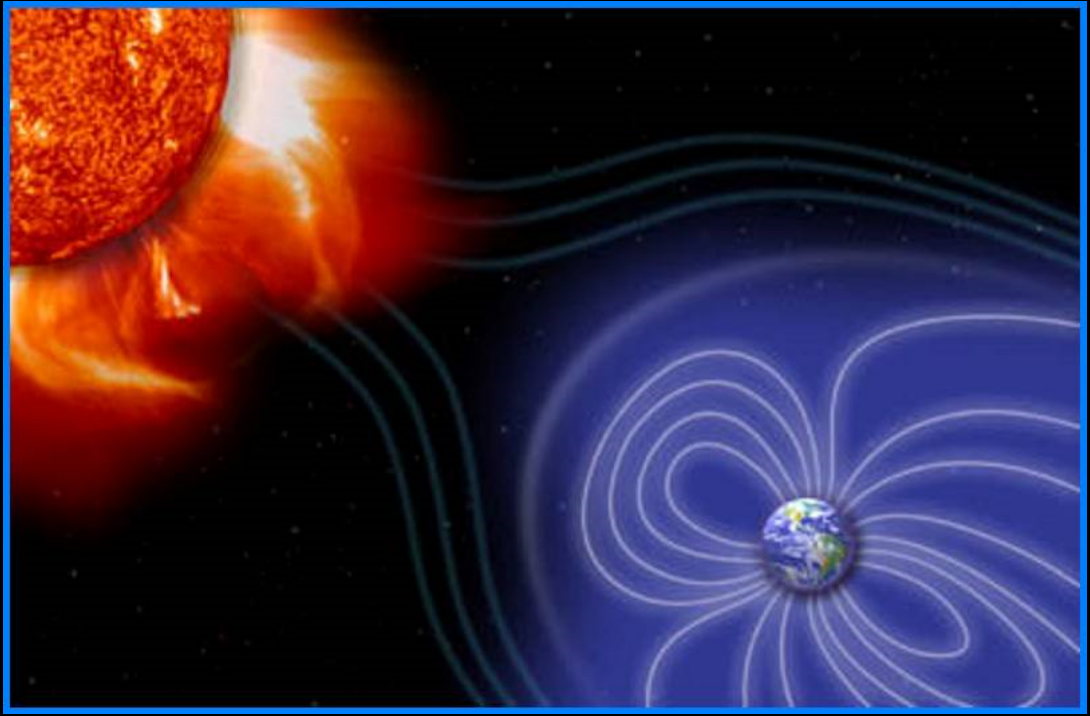
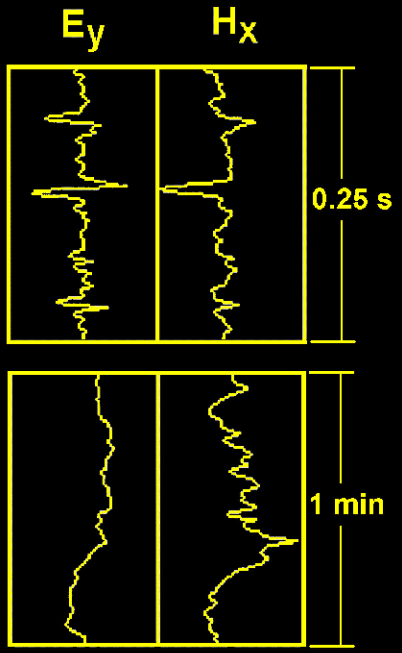
U.S. National Science Foundation, U.S. Department of Energy

# Source Fields for the Magnetotelluric Method






Regional and Global Lightning Activity for f > 1 Hz
Solar Wind-Magnetospheric Interactions for f < 1 Hz

# Outline

<u>Incl. Historical Perspectives</u>

-MT Concepts Dev at MIT (T. Madden)

Tensor relation, Current Channeling, Staggered Grid 3D Modeling

*Vertical current channeling insights into crustal rheology and geothermal systems, Current 3D inversion platforms*

-Concepts Dev at UT Austin (F. Bostick)

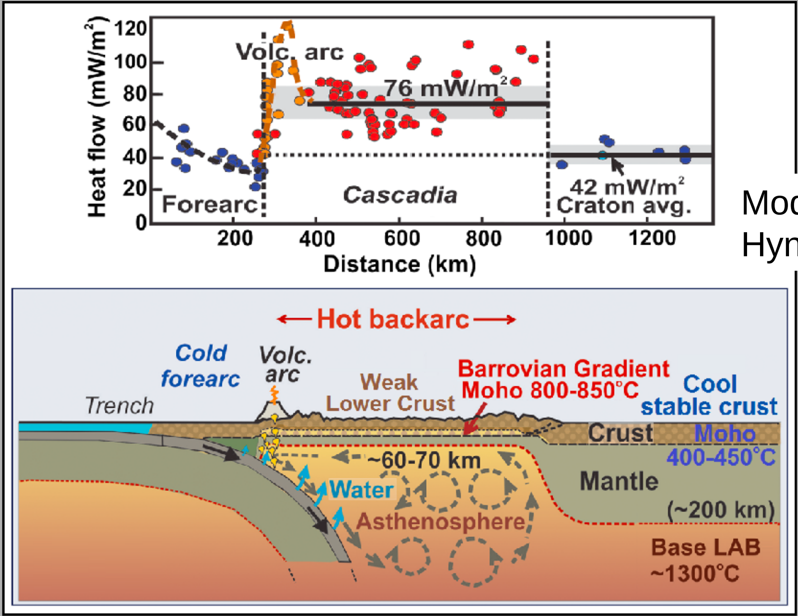
Spectral Estimation, Cascade Decimation, Electromagnetic Array Profiling

*Coherency sorting, Ultra-remote referencing*

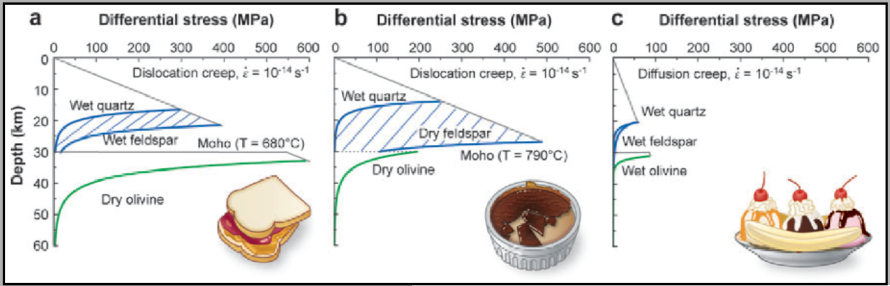
-Aqueous phase controls in lower crust and upper mantle

-MT surveying in polar regimes

## Subduction/Backarc Extension and Continental Growth




Modified from Hyndman (2018)




Burgmann and Dresen (2008)

$$H_2 = \alpha_{21}E_1 + \alpha_{22}E_2$$
$$H_1 = \alpha_{11}E_1 + \alpha_{12}E_2$$

## Cantwell (1960, MIT)

Recognition of need for tensor relation

$$\begin{pmatrix} \mathrm{I} \\ \mathrm{II} \end{pmatrix} \qquad \begin{pmatrix} \mathrm{I} \\ \mathrm{II} \end{pmatrix} \qquad \begin{pmatrix} \mathrm{I} \\ \mathrm{II} \end{pmatrix}$$
$$\Phi_{h_1h_1}(\theta) = Y_{11}(\theta)\Phi_{h_1e_1}(\theta) + Y_{12}(\theta)\Phi_{h_1e_2}(\theta)$$
$$\begin{pmatrix} \mathrm{I} \\ \mathrm{II} \end{pmatrix} \qquad \begin{pmatrix} \mathrm{I} \\ \mathrm{II} \end{pmatrix} \qquad \begin{pmatrix} \mathrm{I} \\ \mathrm{II} \end{pmatrix}$$
$$\Phi_{h_2h_2}(\theta) = Y_{21}(\theta)\Phi_{h_2e_1}(\theta) + Y_{22}(\theta)\Phi_{h_2e_2}(\theta)$$

$$E_j(\theta) = \beta_{jk}E_k(0)$$
$$H_i(\theta) = \beta_{ik}H_k(0),$$
$$[\beta_{ik}] = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

## Bostick and Smith (1962, UTA)

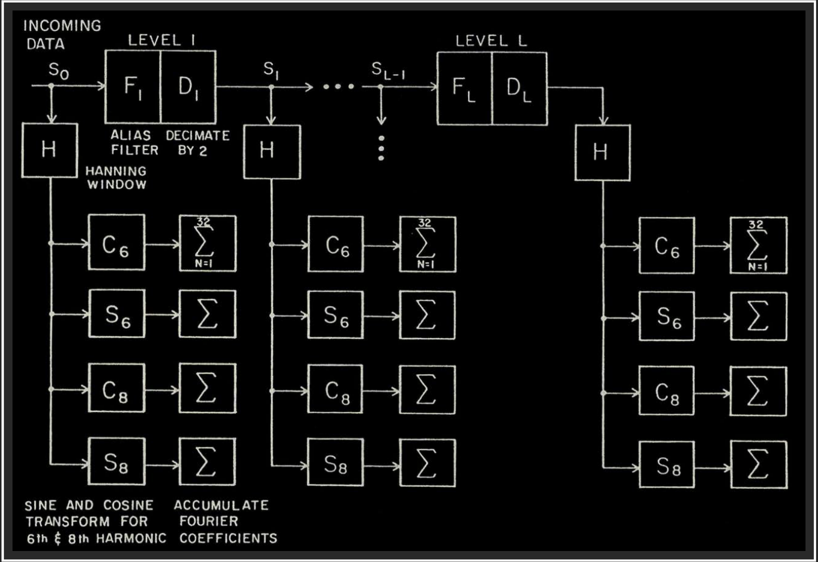
Impedance elements from spectral cross powers

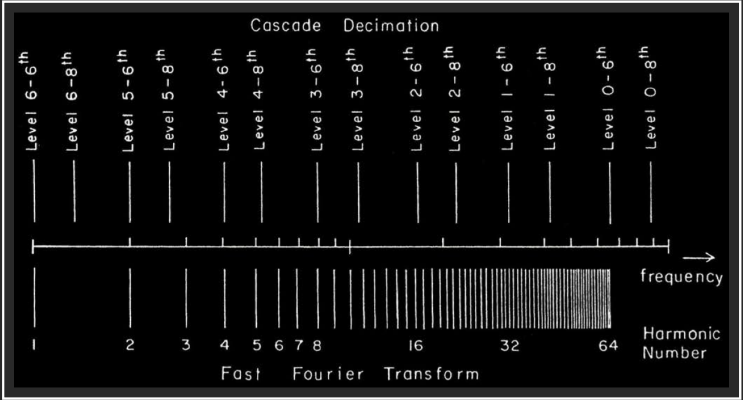
$$Z_{xy} = \frac{(H_x H_x^*)(E_x H_y^*) - (E_x H_x^*)(H_x H_y^*)}{(H_x H_x^*)(H_y H_y^*) - (H_y H_x^*)(H_x H_y^*)}$$

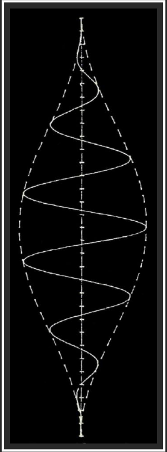
## Sims et al (1971)

## Wight et al (1977, UTA)

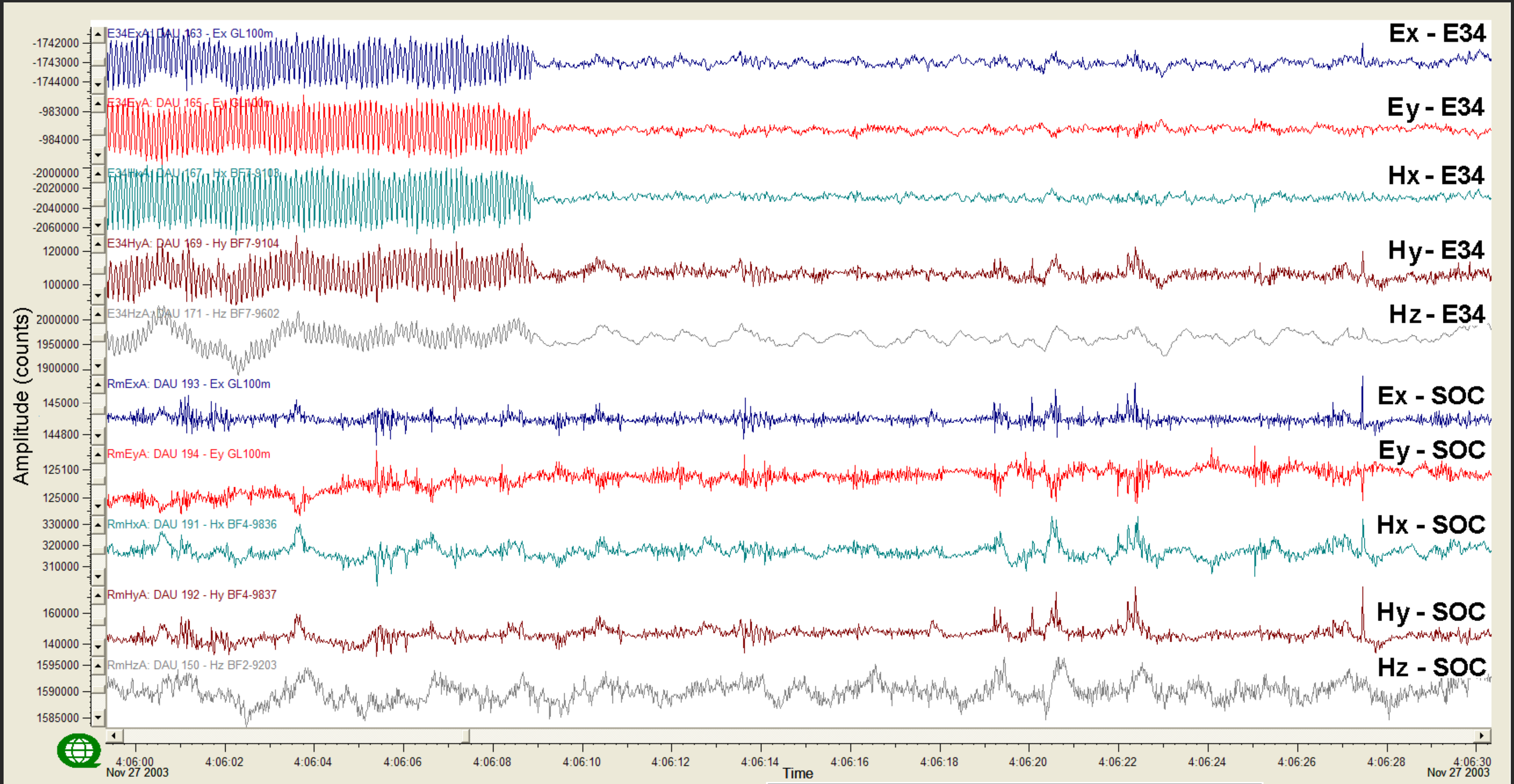
Cascade decimation and RT FT



Cascade vs FFT log frequency spacing

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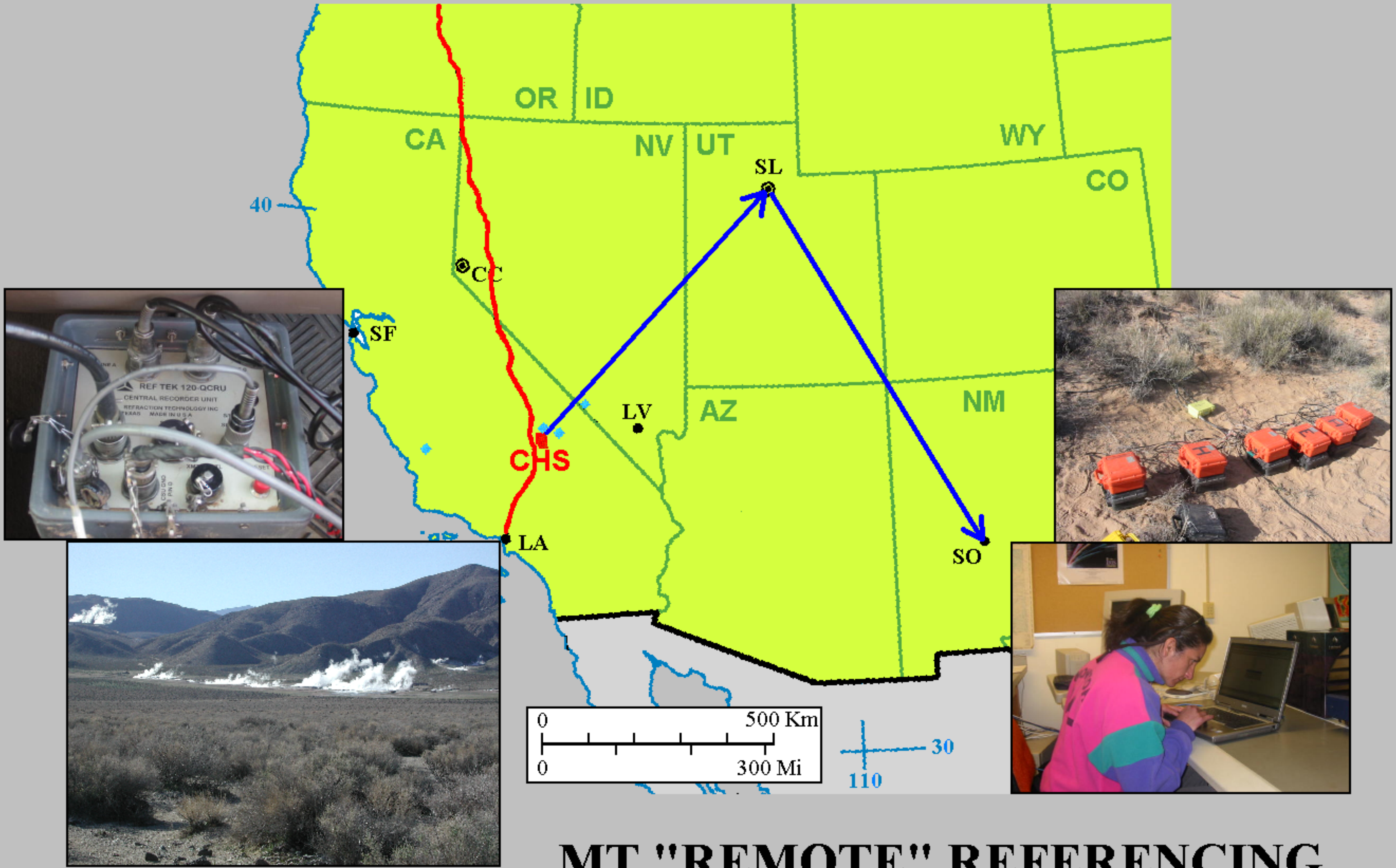
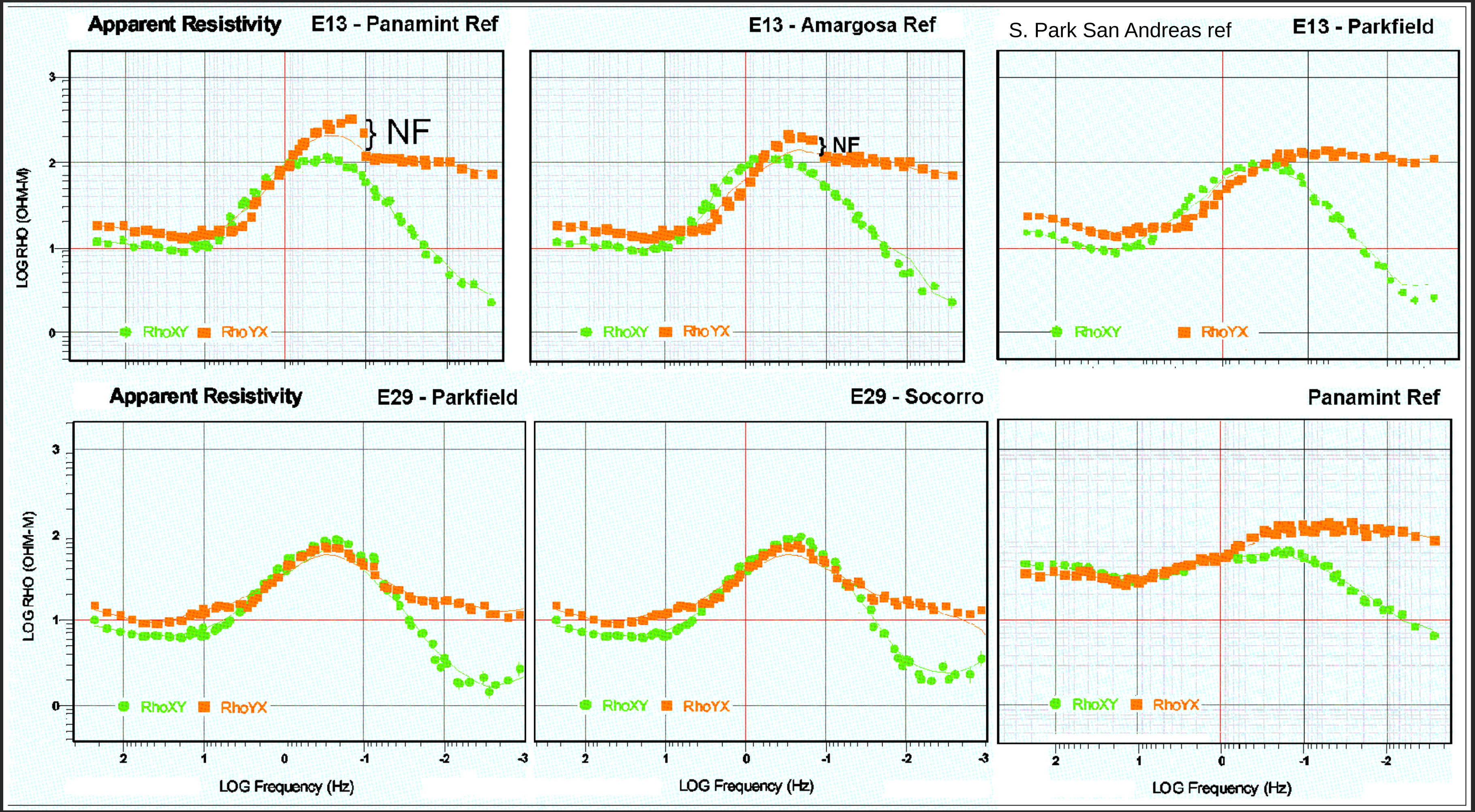
# Local (noisy) vs Remote MT time series

Coso Geothermal Field (Wannamaker et al, 2004)

Clarke, Gamble, Goubau (1978)



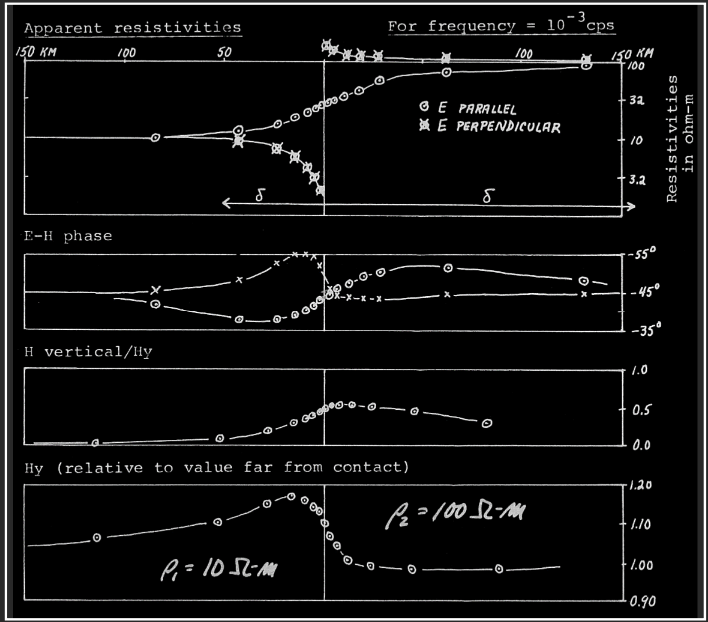

# MT "REMOTE" REFERENCING



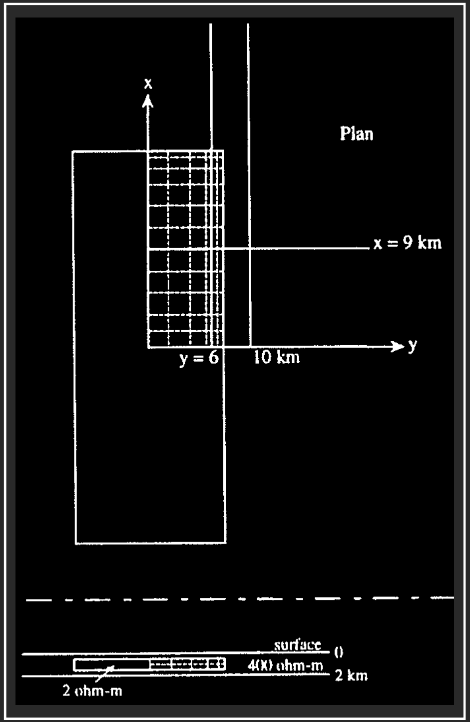

DC intertie near-field effect exceeds 150 km. Reference must be completely outside its field span even if plane wave by that point.

# Swift (1967, MIT)

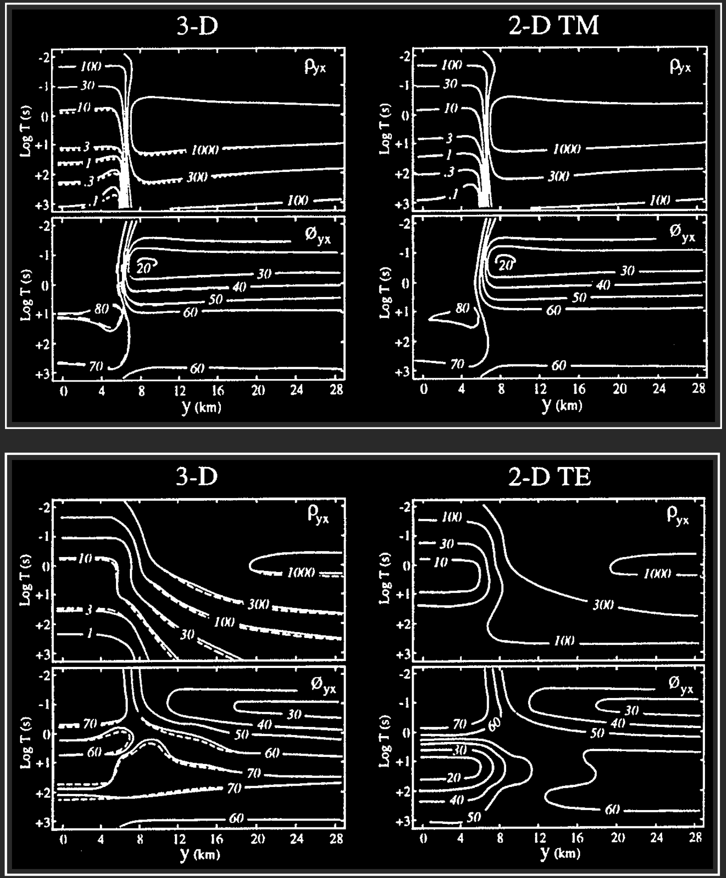
-Assumed tensor relation from start
-Elliptical traces in complex plane
-Spectral analysis from time segments
-Specified TE, TM modes




-Collected 7 tensor sites in AZ and NM using ~50 km telephone lines; T = ~1000 s to ~1 da
-2D forward modeling using FD code
-Deeper upper mantle 10-30 ohm-m
*-Noted that “TE” response inside truncated graben could be depressed*




Wannamaker, Hohmann and Ward (1980, 1984); Ledo (2005)




Similarity of 3D Zyx and 2D TM for simple bodies, incl. off-center
Disagreement of 3D Zxy and 2D TE due to boundary charges
More complex bodies increasingly 3D

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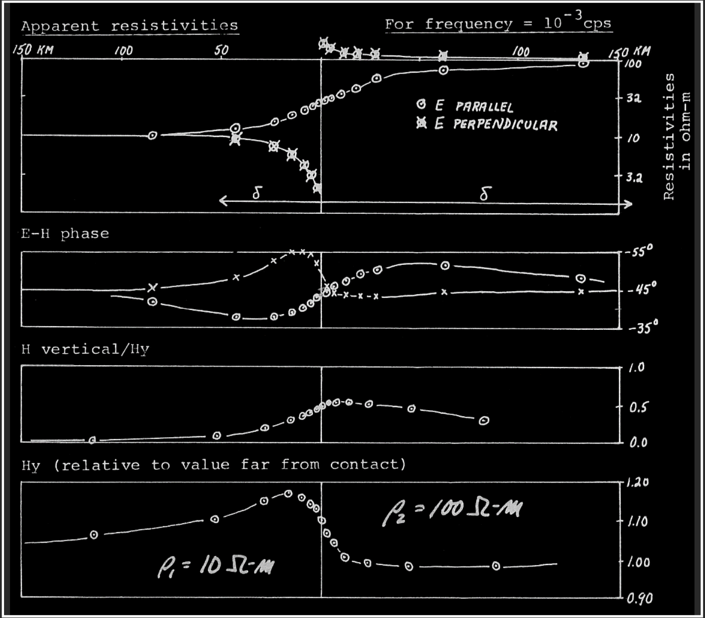


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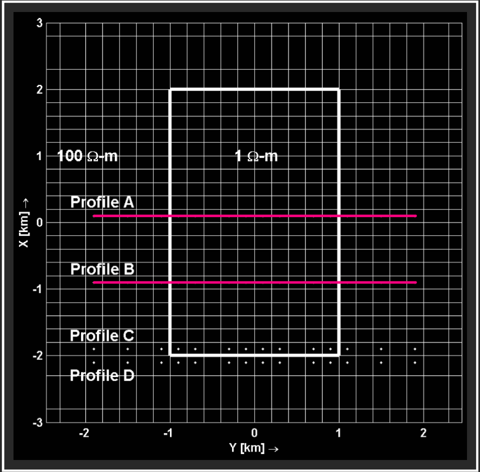
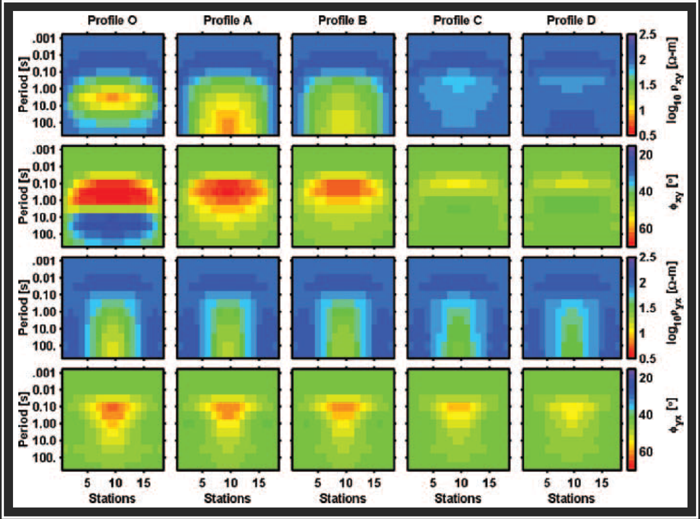
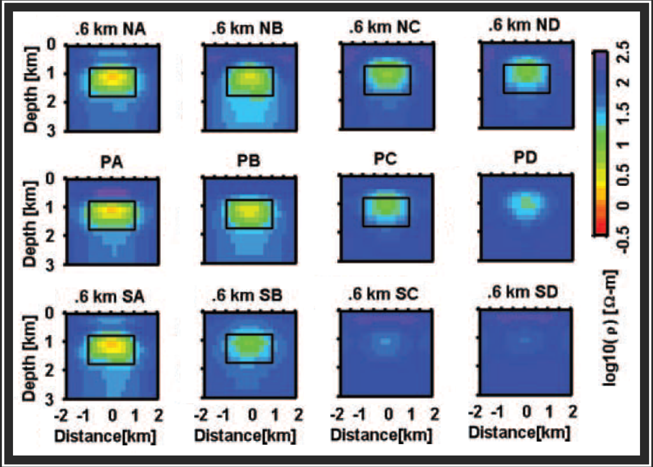
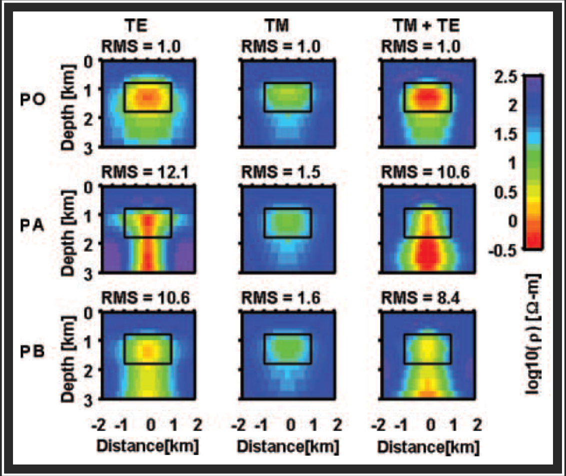



Siripunvaraporn et al, (2005)

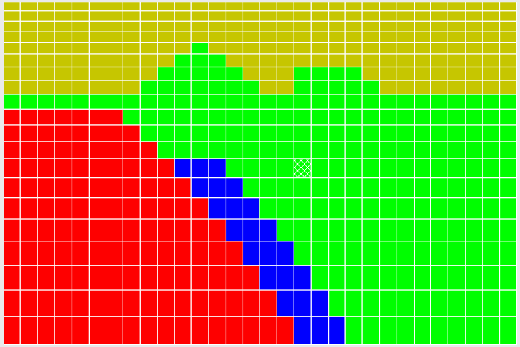



3D Profile Inversion Effective



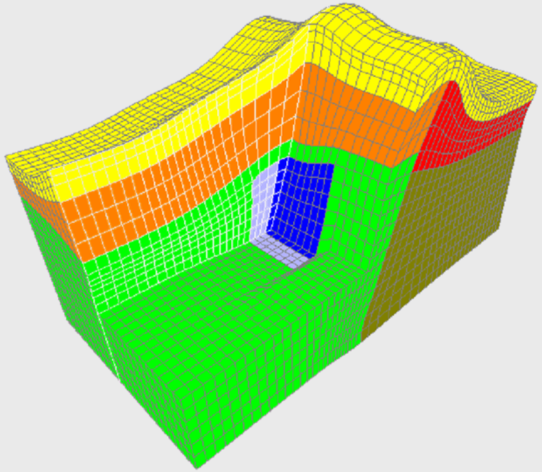

2D "TE" Inversion Distorted

# Electromagnetic Simulation and Inversion With Conformal Receiver Surfaces (Topography)

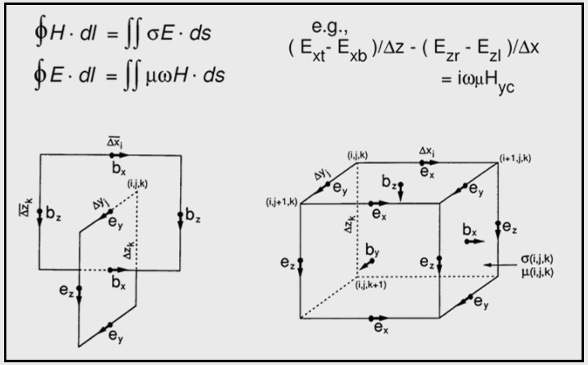


**Finite Difference Topo Model**

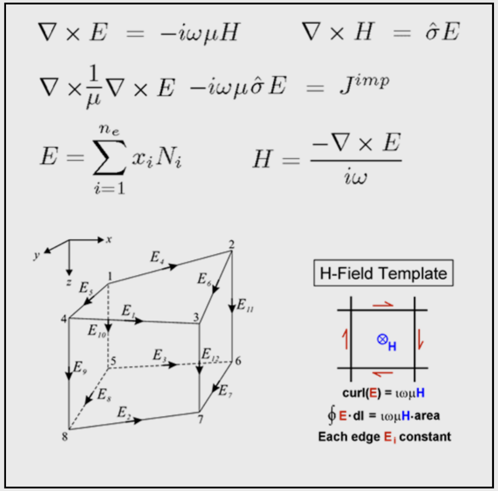
*Graphics after Art Raiche*



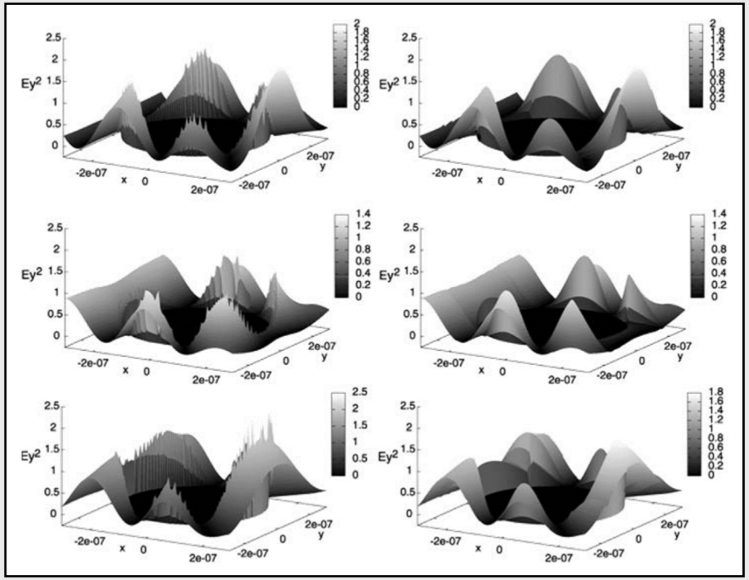
**Finite Element Cutout View**

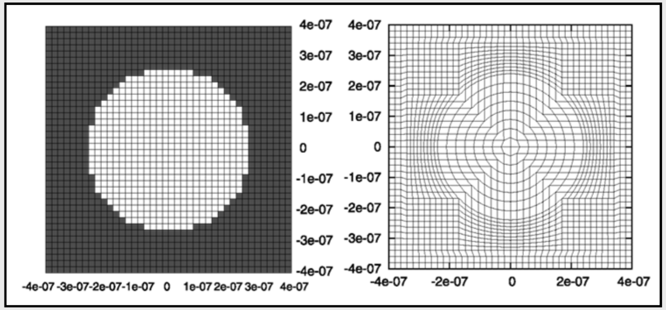



**FD: Madden and Mackie (1989) resurrected Yee (1966) staggered grid. Numerous followers.**



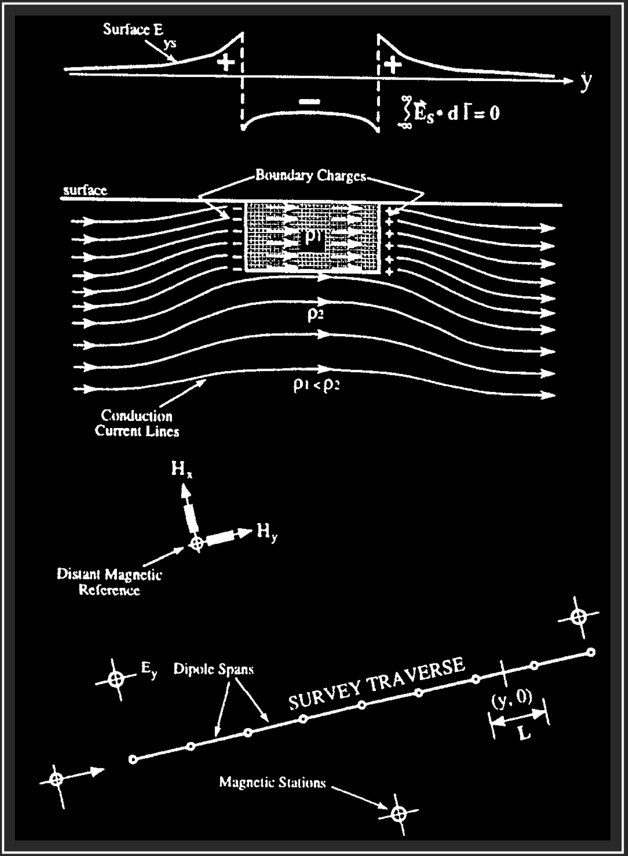

**FE: E-field discontinuity treated with edge elements. Unambiguous placement of sharp interfaces.**

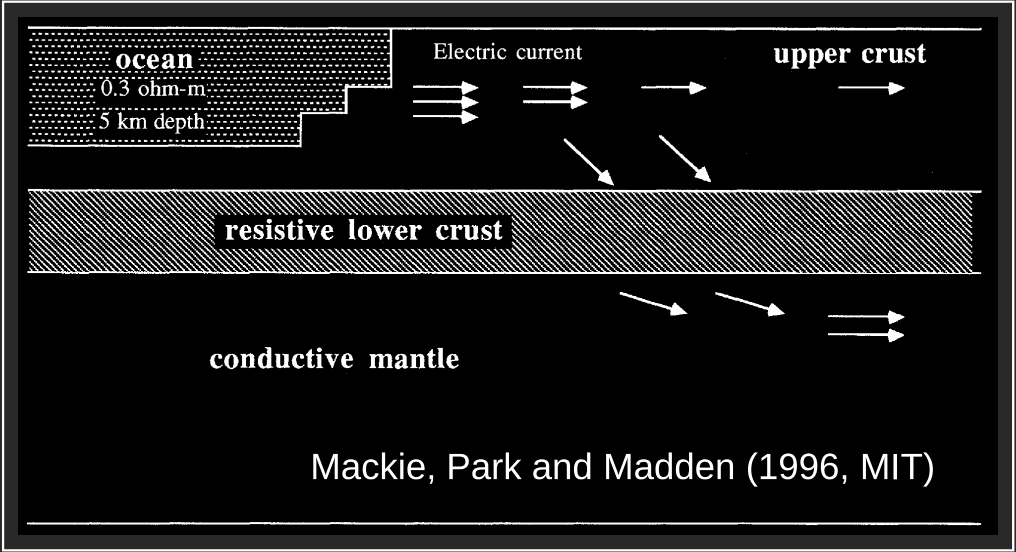


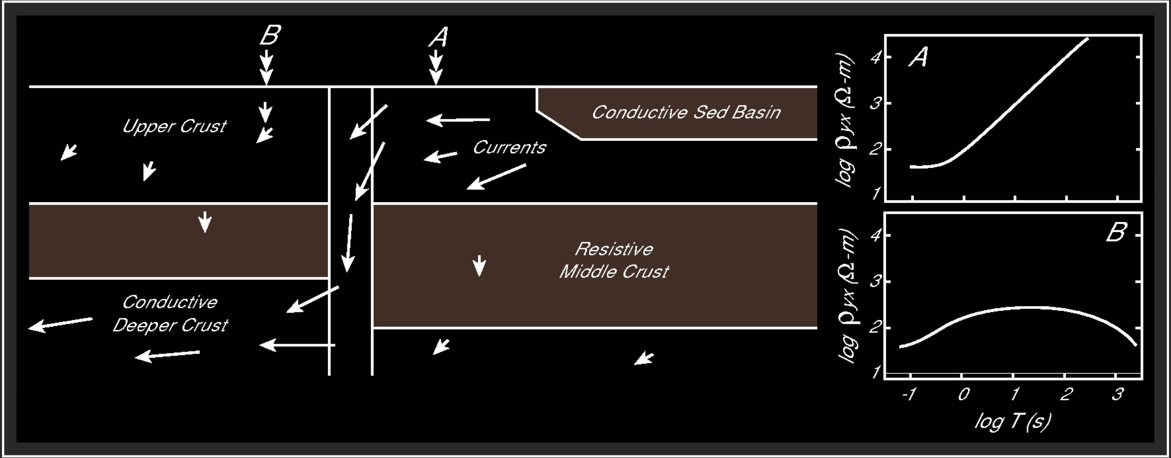




Scattered E Power
Liu et al., 2009

Torres-Verdin and Bostick (1992, UTA)
-Sampling challenge in natural environs
-E-field anomalies zero-mean, incl. 3D



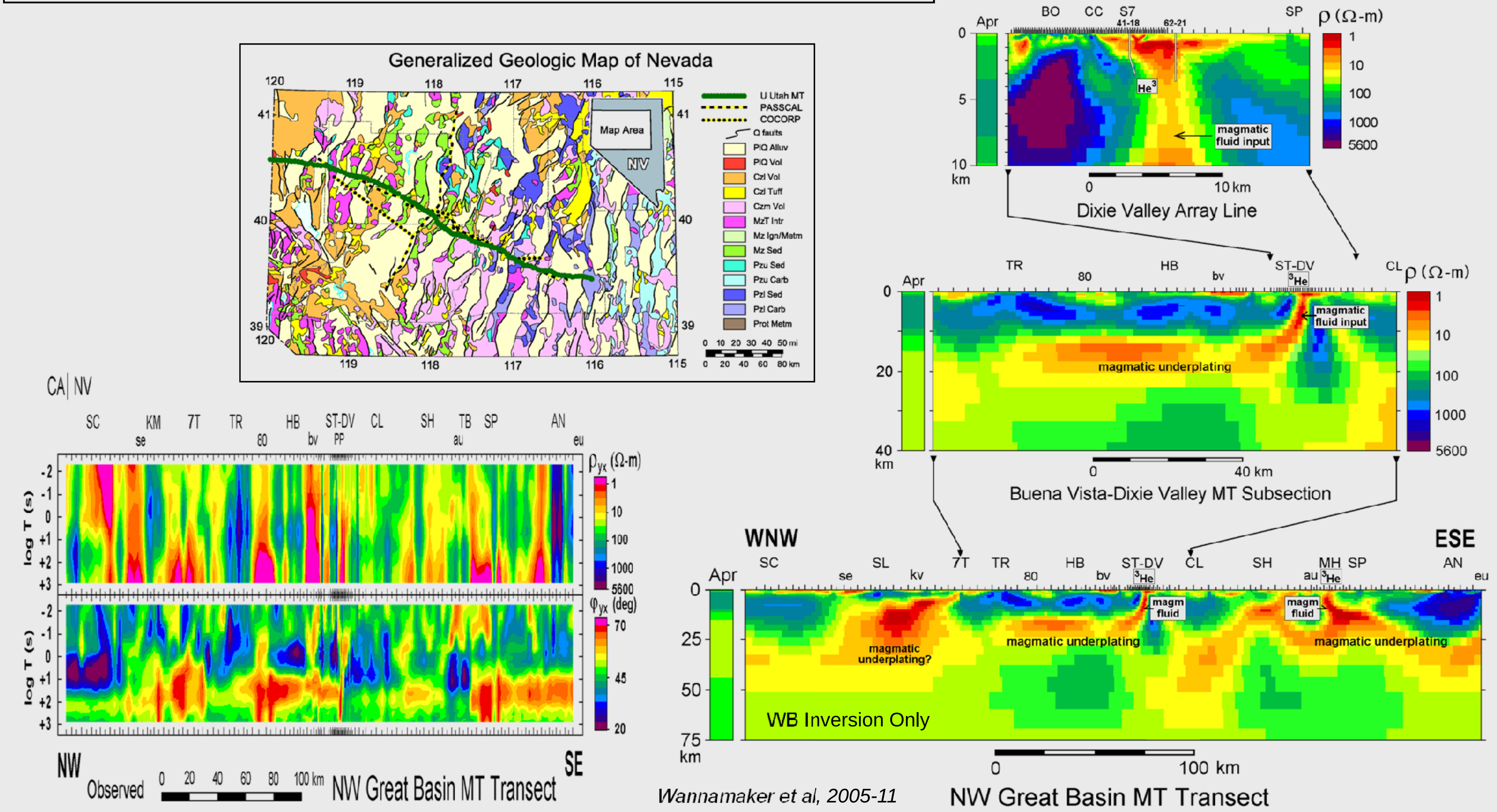




Vertical Current Channeling down Crustal-Scale Fault Zone

-Thus both Zxy and Zyx are zero-mean
-Zav = [Zxy – Zyx]/2 a logical background

# Crustal-Scale Breaks and Multiscale Magmatic/Hydrothermal Connections




*Wannamaker et al, 2005-11*

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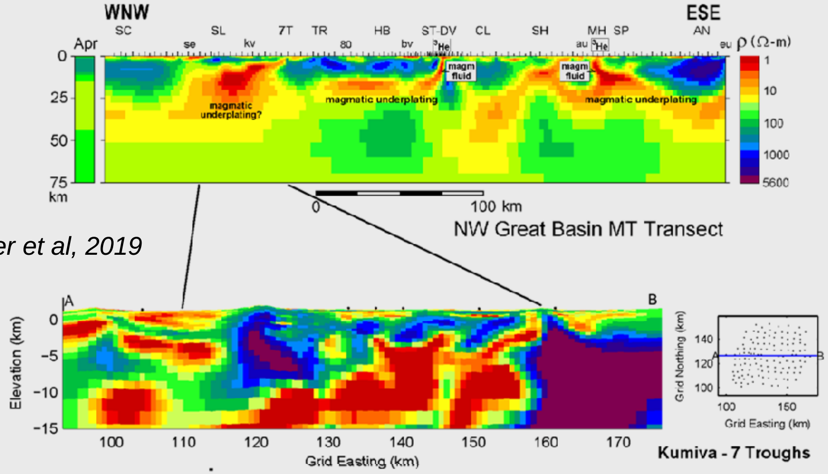
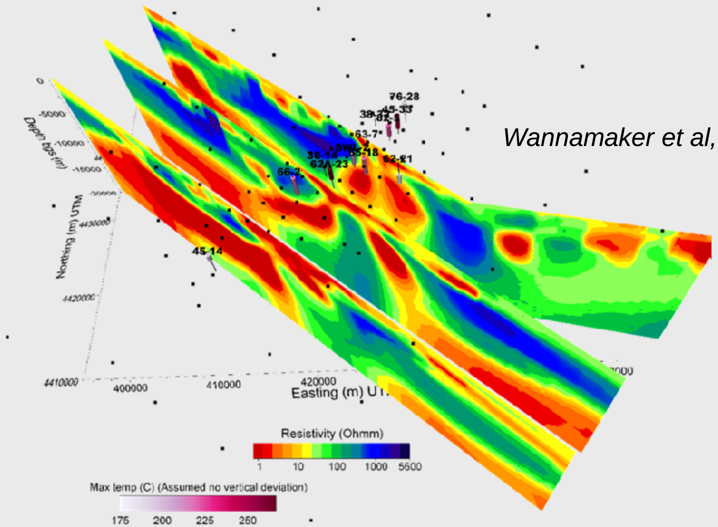
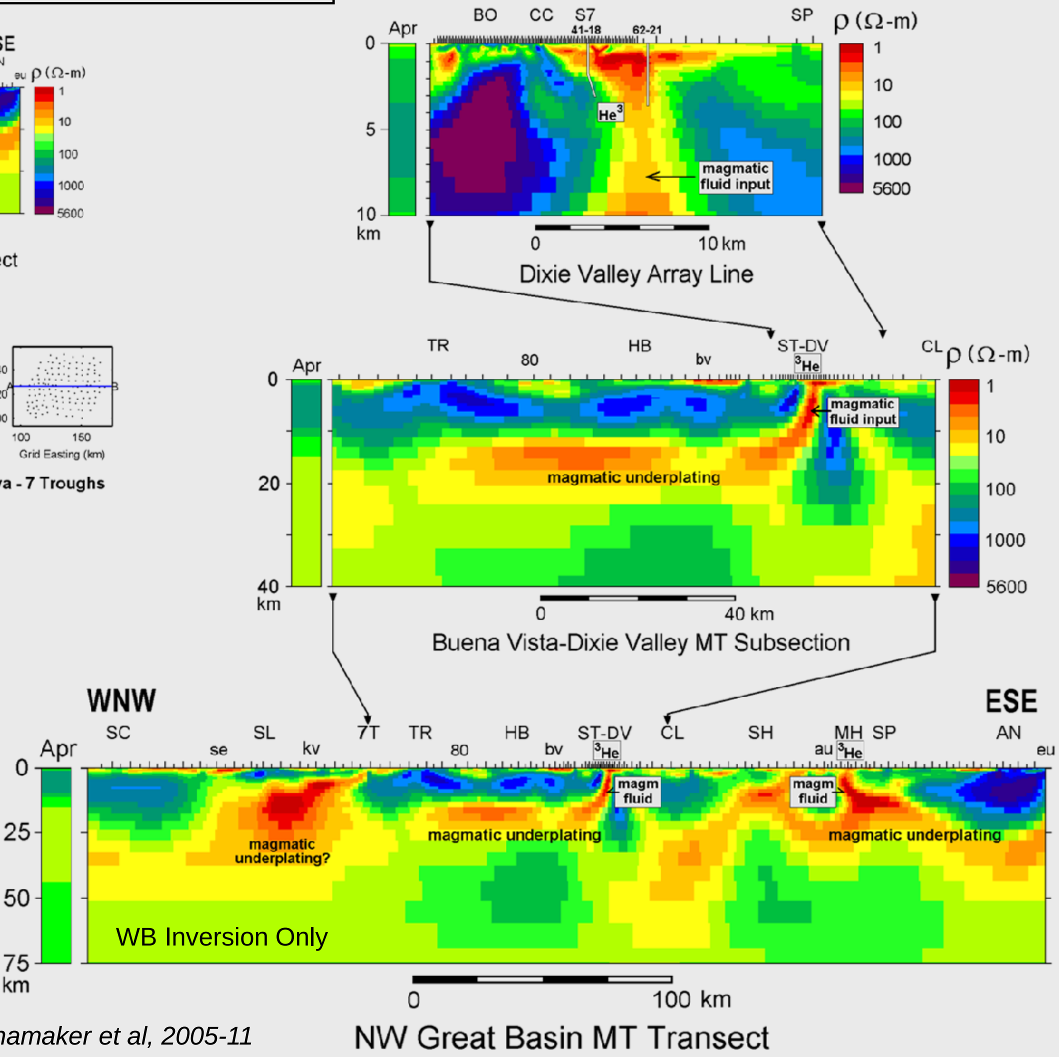



*Wannamaker et al, 2019*




*Wannamaker et al, 2013*

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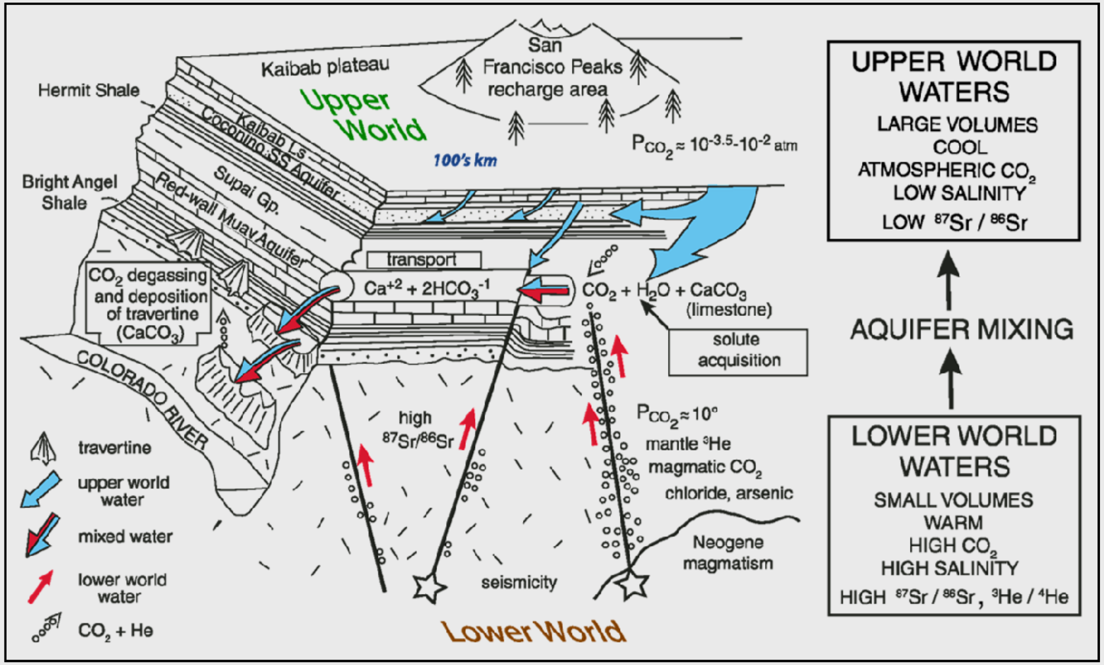
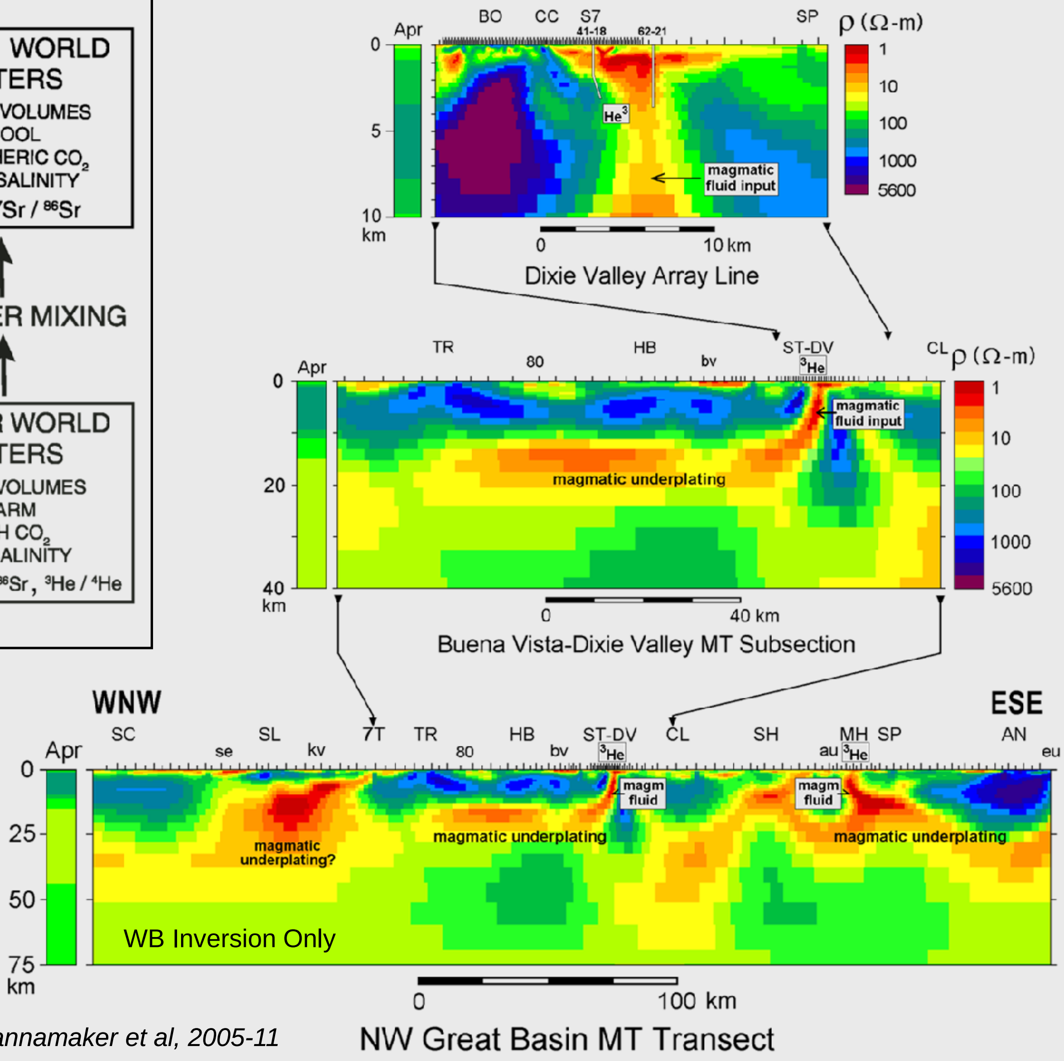


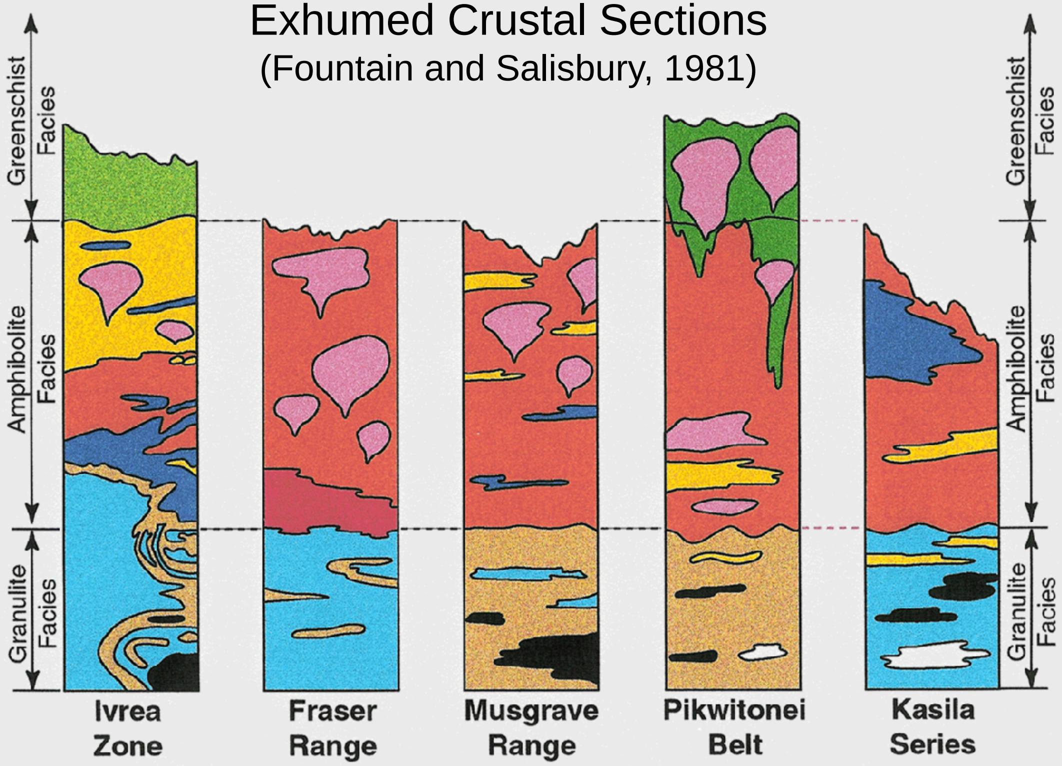

# Multiscale Magmatic/Hydrothermal Connections

Grand Canyon Hydrological Model
(Crossey and Karlstrom, 2012)

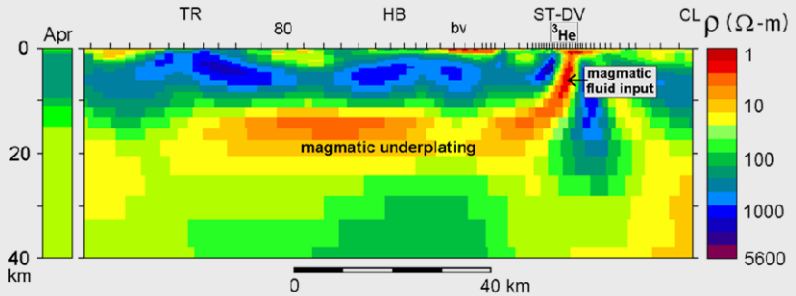



*Wannamaker et al, 2005-11*

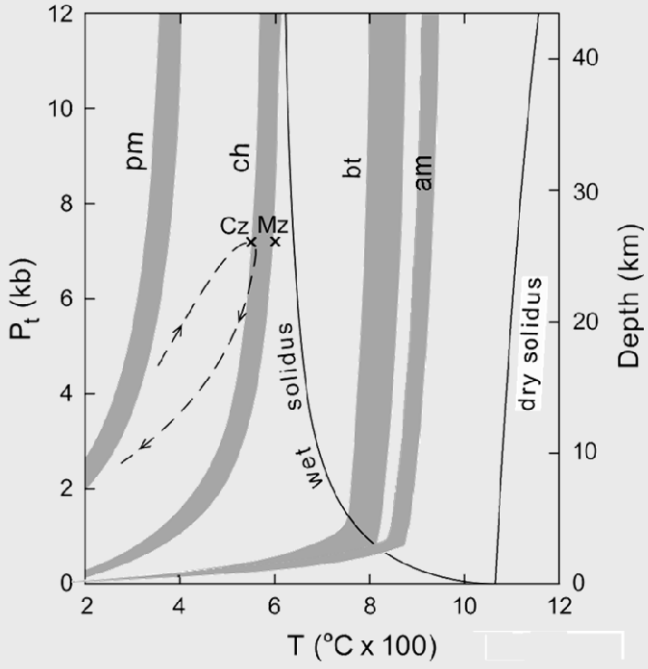
# Exhumed Crustal Sections
(Fountain and Salisbury, 1981)




- Free water not compatible with granulite-upper amphibolite facies- resorbed to more amph/biotite
- Any present fluid must be of low a(H2O)
- Complex salts may provide a mechanism
- Comment/Reply Yardley (1997, 2000), Wannamaker (2000)




Buena Vista-Dixie Valley MT Subsection




Diorite-H2O petrogenetic grid

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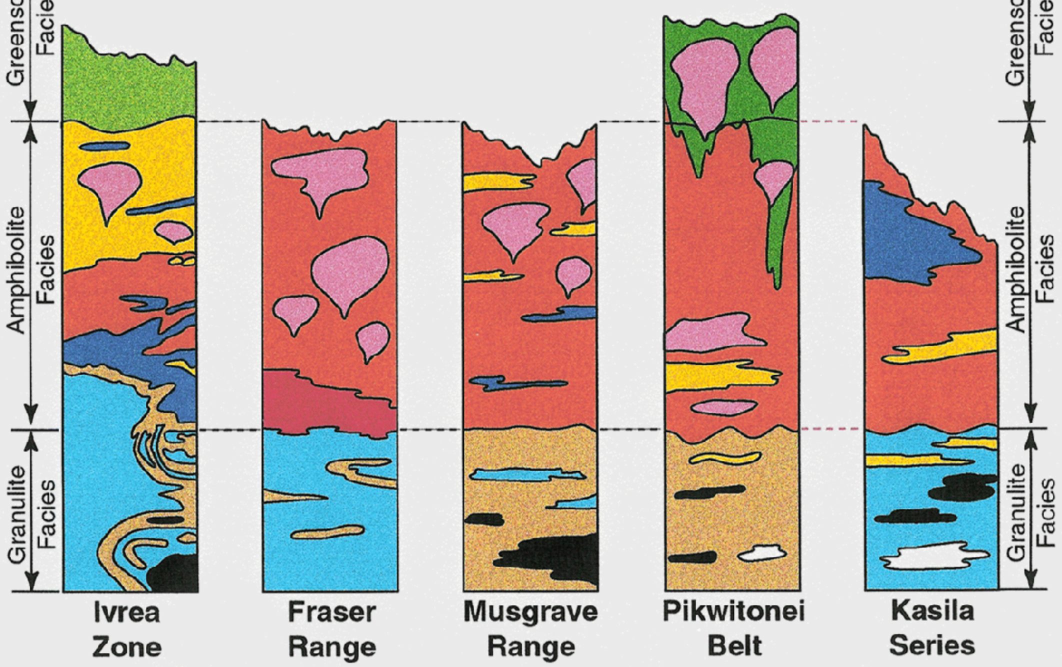


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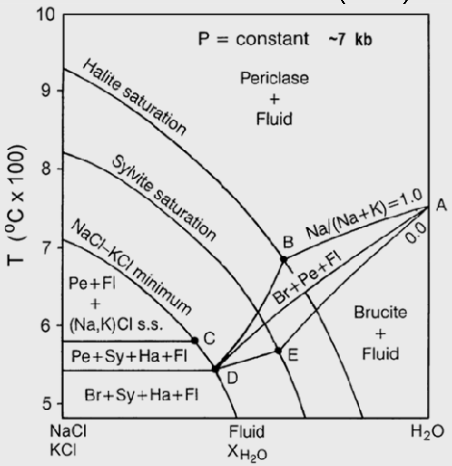
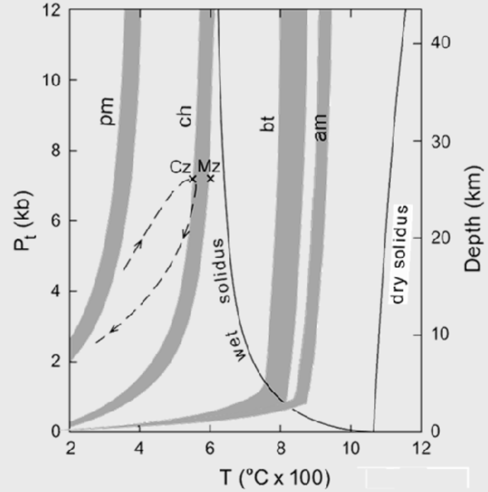
Aranovich and Newton (1997)




Complex salts reduce T of last fluid

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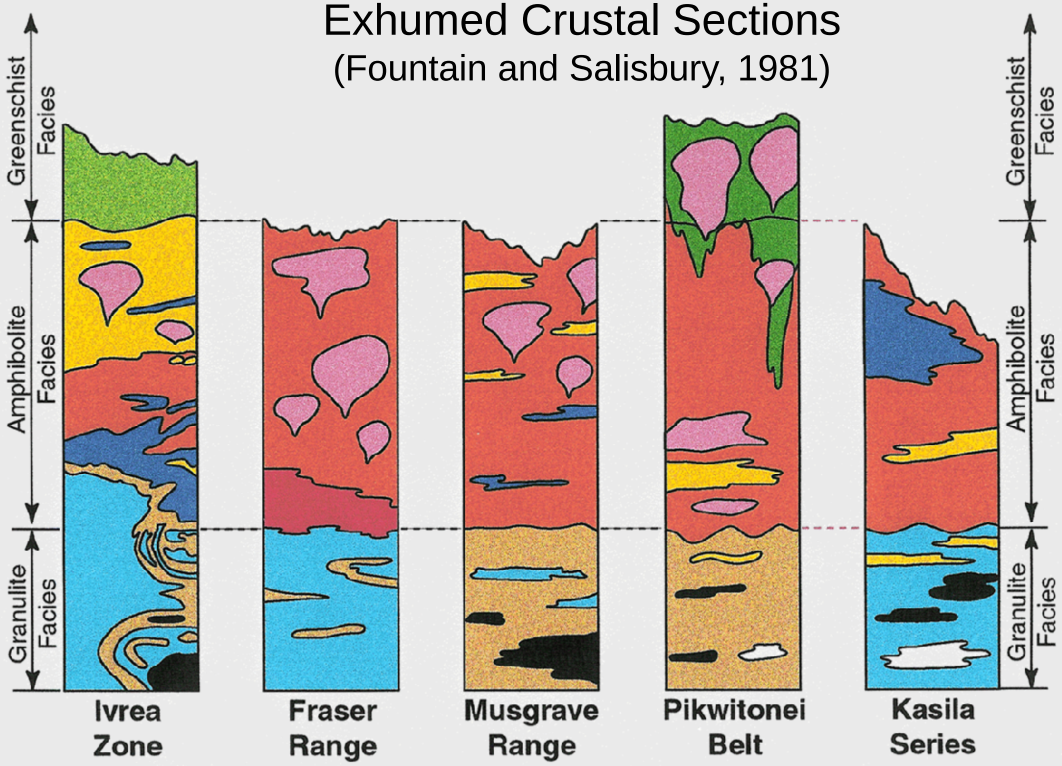


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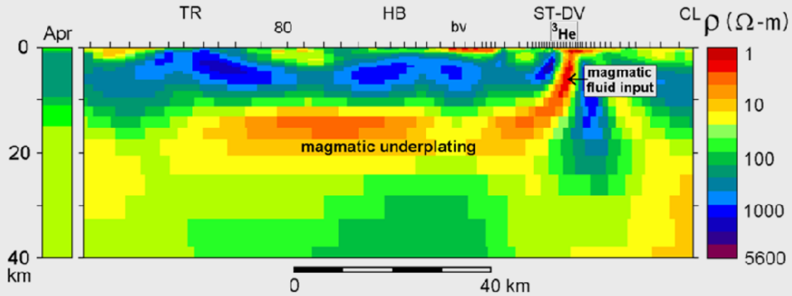


Buena Vista-Dixie Valley MT Subsection

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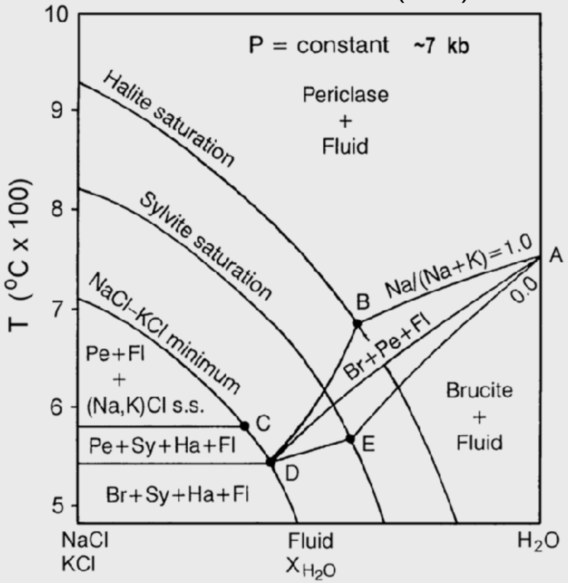


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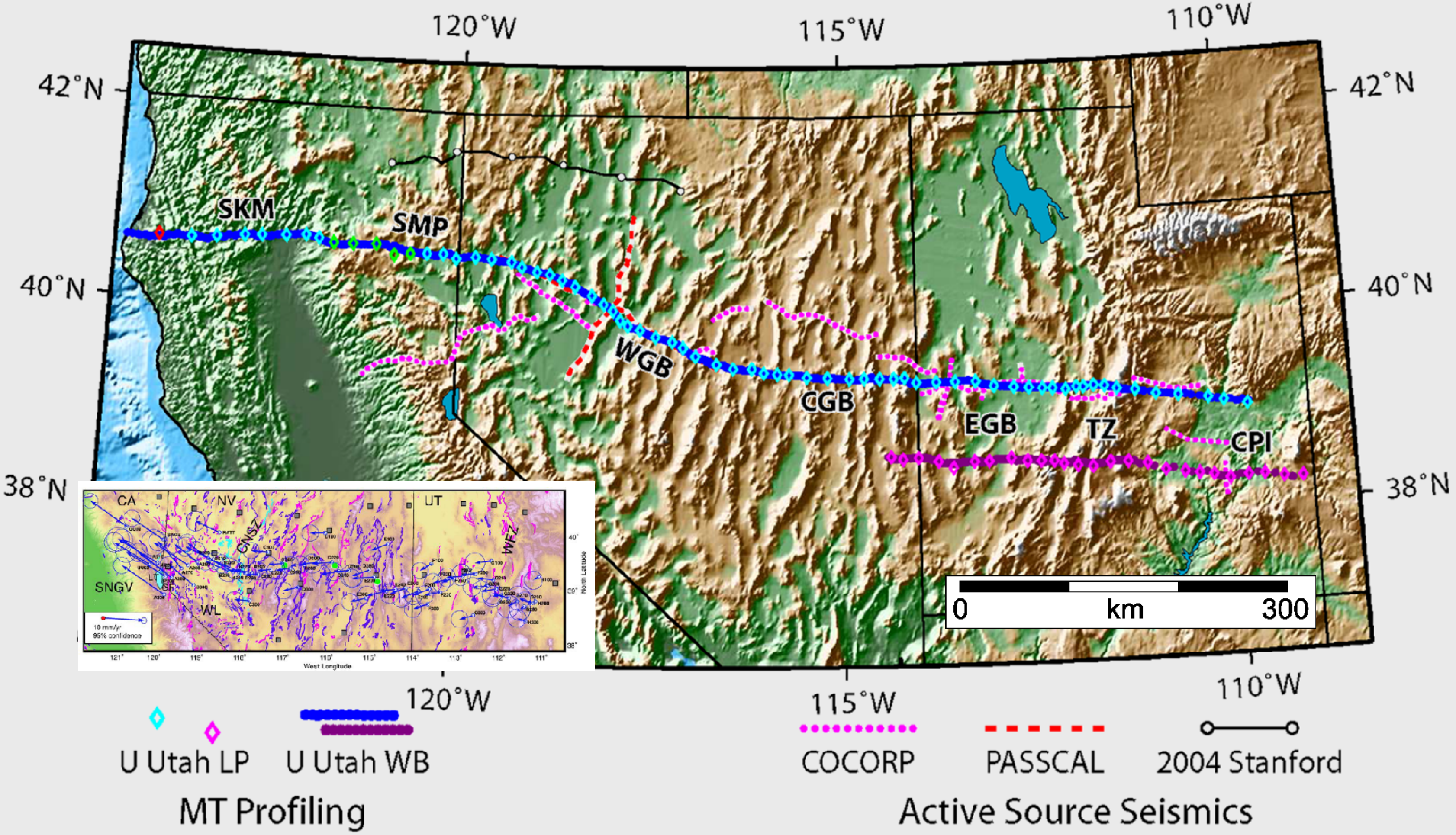
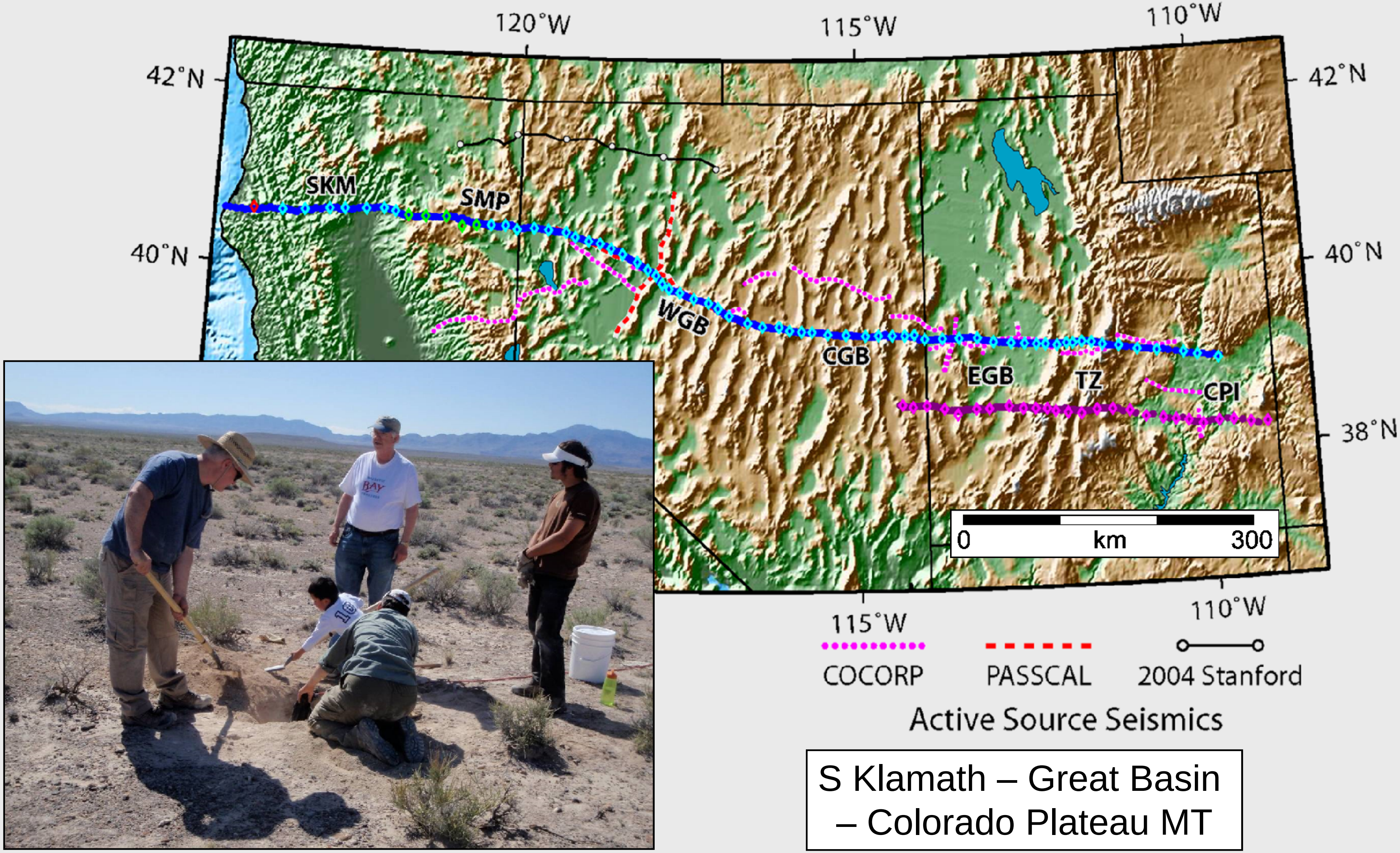
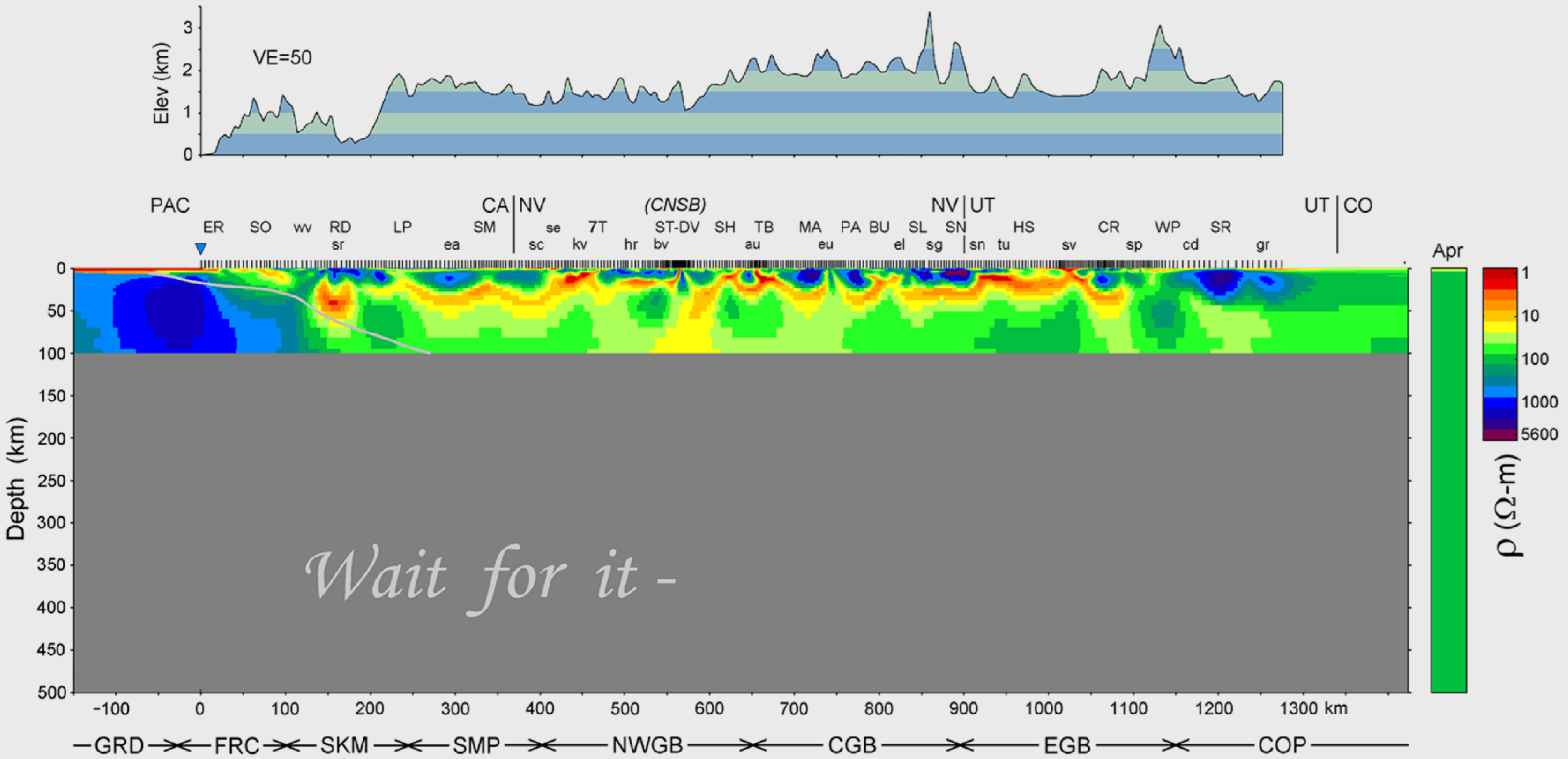



# S Klamath Mtns – Great Basin – Colorado Plateau MT

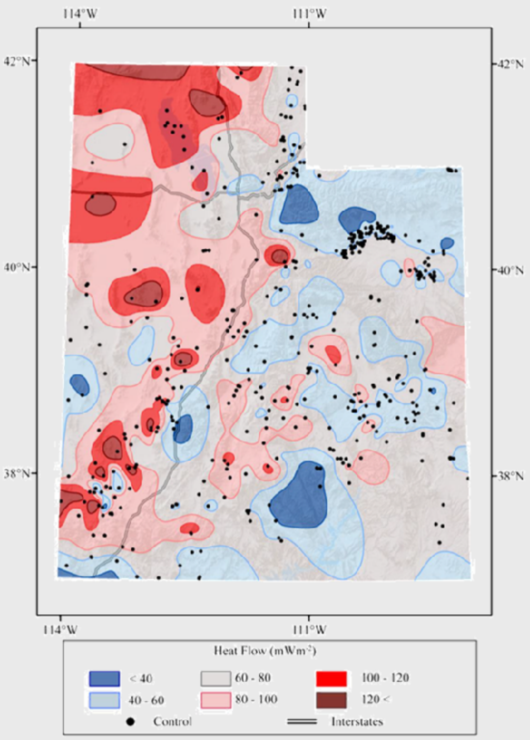
Approx. coincident with COCORP, PASSCAL seismic profiling

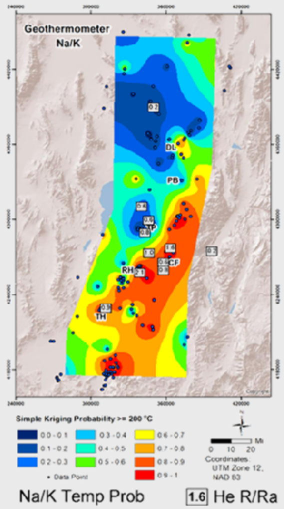


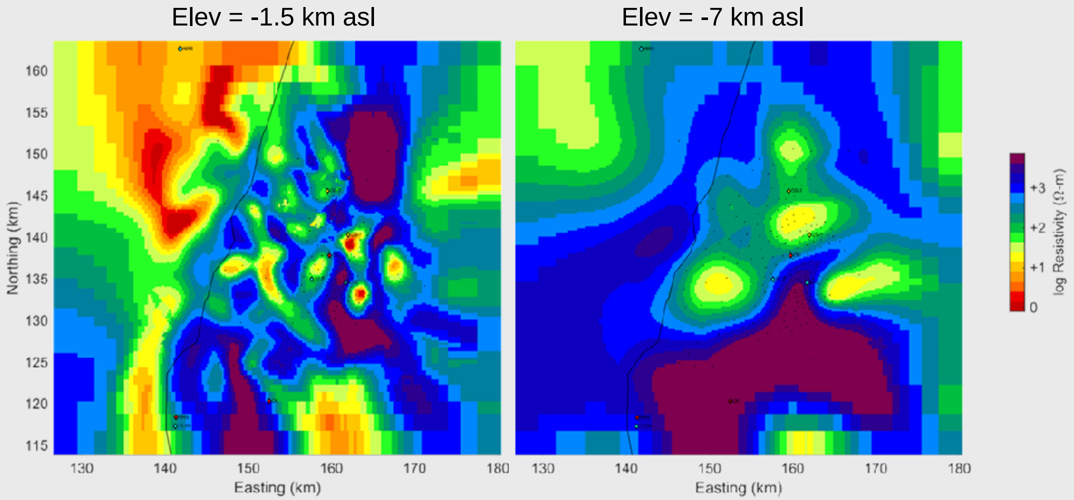

S Klamath – Great Basin – Colorado Plateau MT

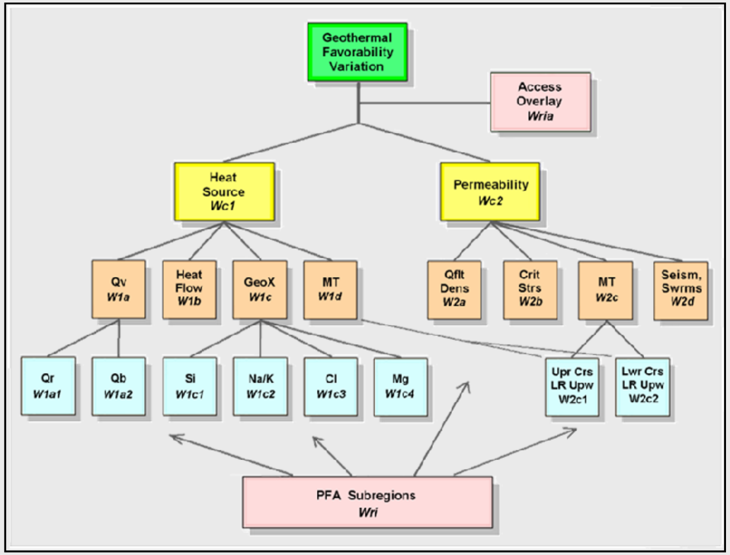


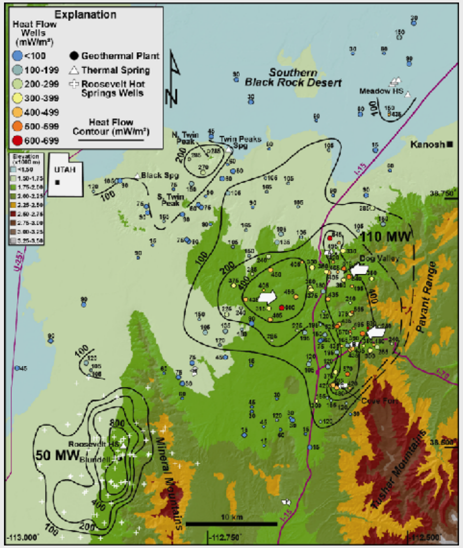

Klamath - S Modoc - Great Basin - Colorado Plateau
MT Transect (~40 N lat.)



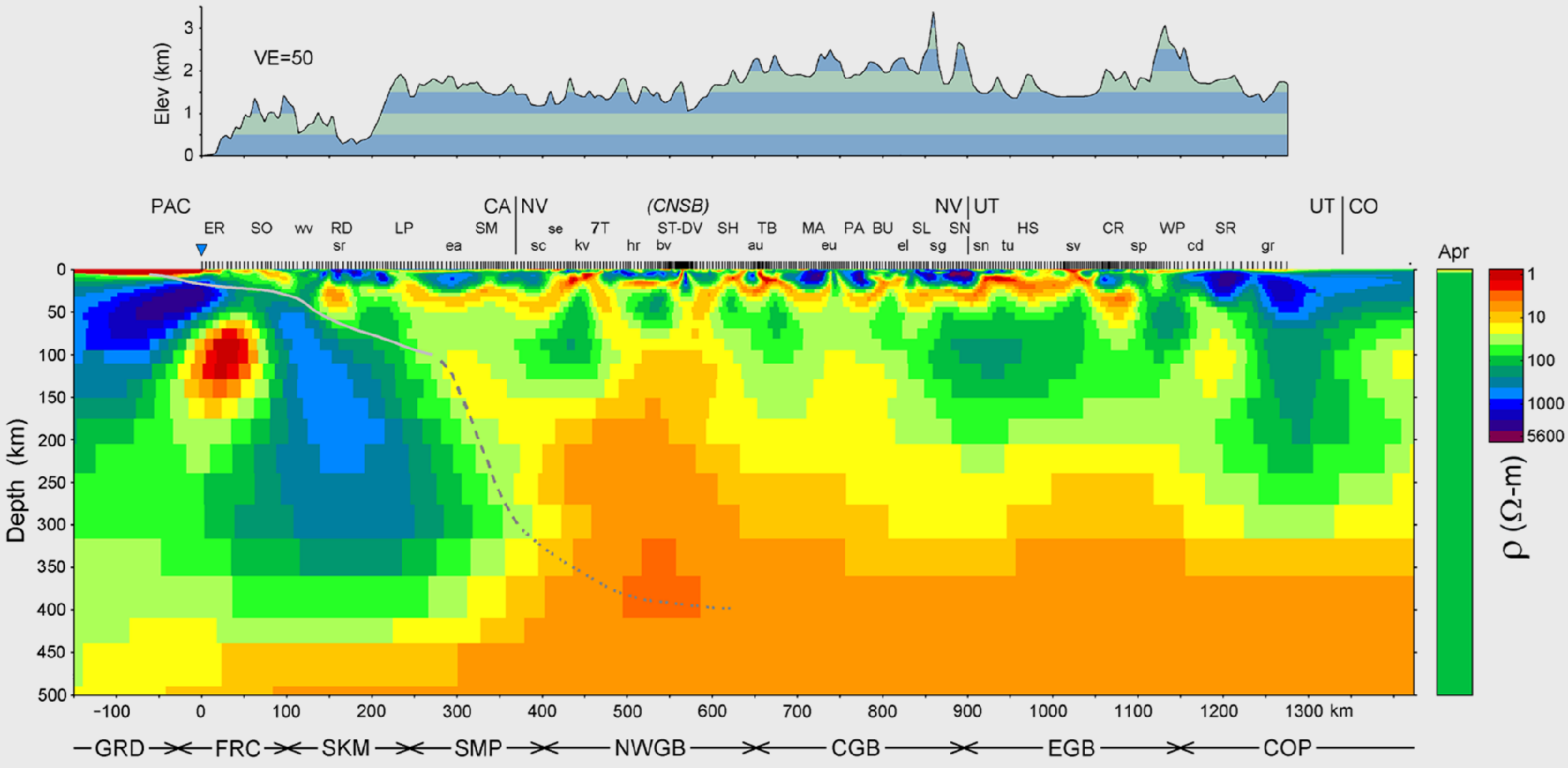




# Multi-Criteria Decision Making (MCDM) Implementation for Geothermal Prospectivity

(Wannamaker et al., 2017)




Klamath - S Modoc - Great Basin - Colorado Plateau
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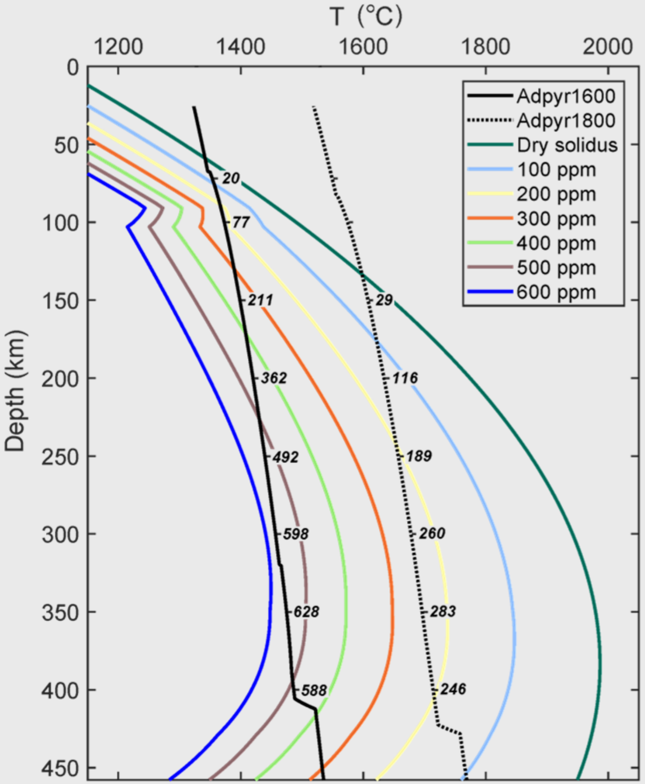
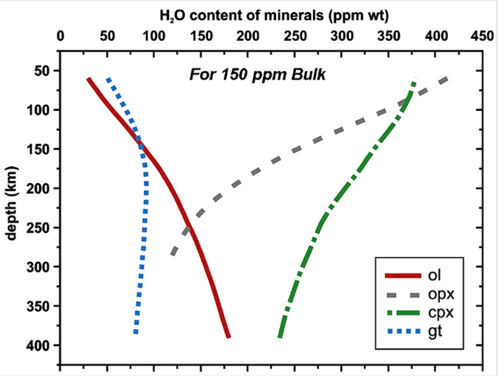
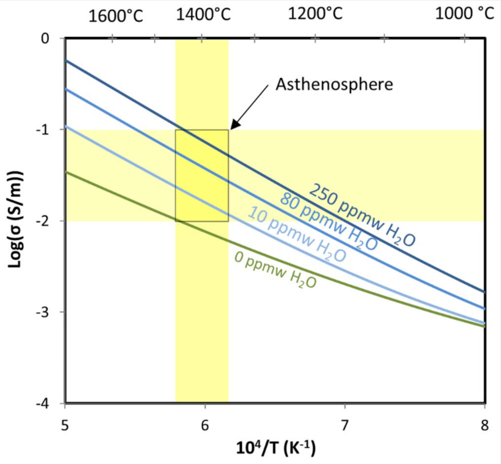


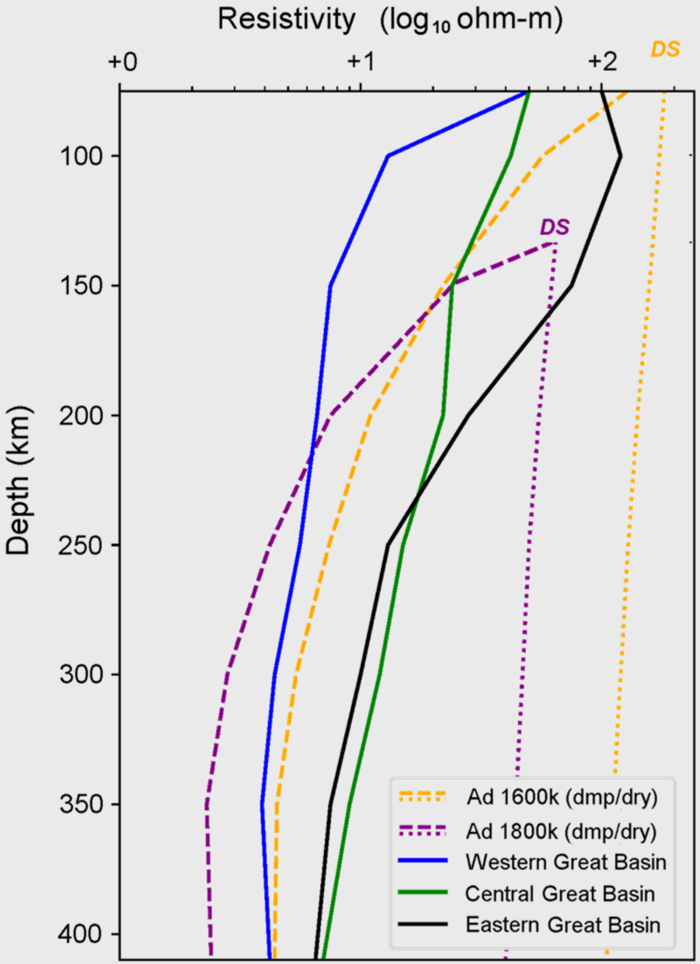

Hirschmann et al (2009, PEPI)
Stixrude and Lithgow-Bertelloni (2011, GJI)

Novella et al (2014, EPSL)



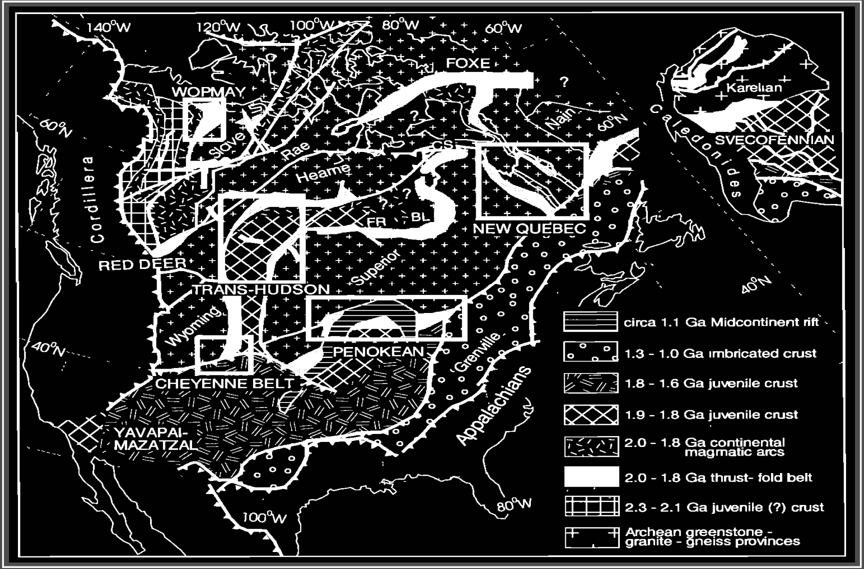

Novella et al (2017, Sci Rpt)

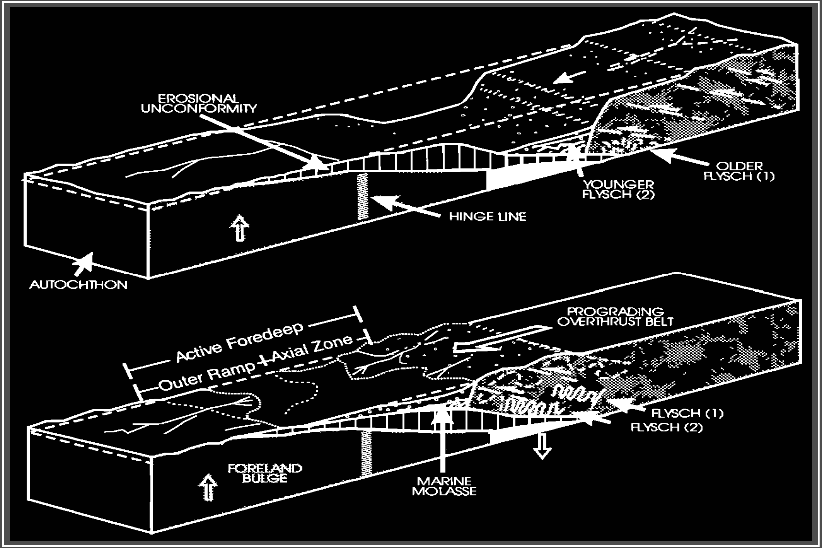


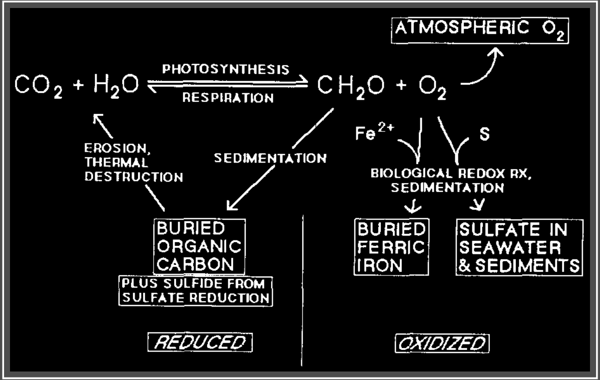
# Electrical conductivity and Paleo-Proterozoic foredeeps

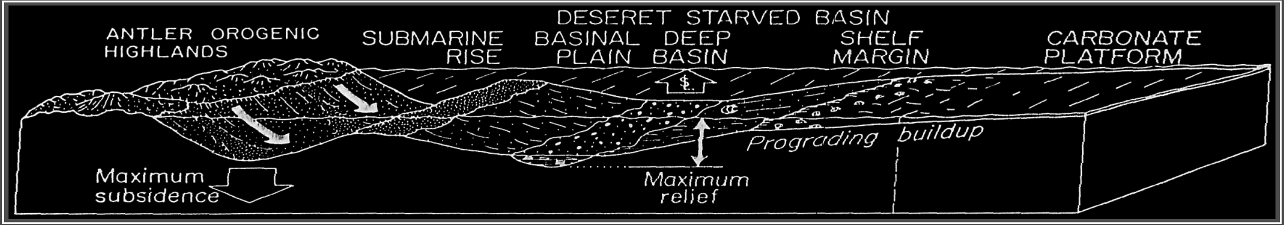
D.E. Boerner, R.D. Kurtz, and J.A. Craven

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. B6, 1996



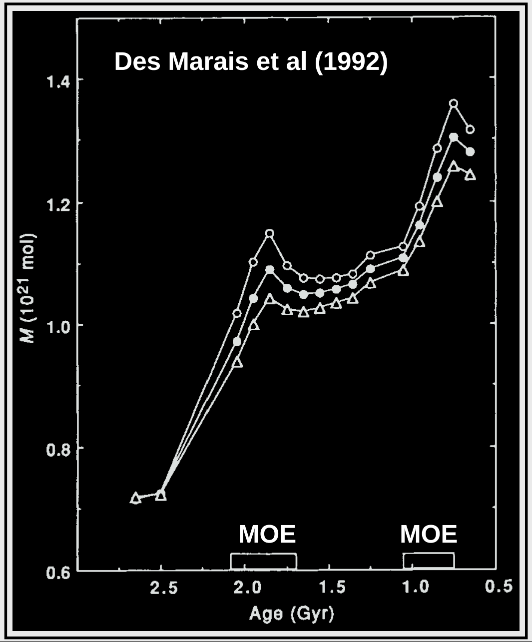



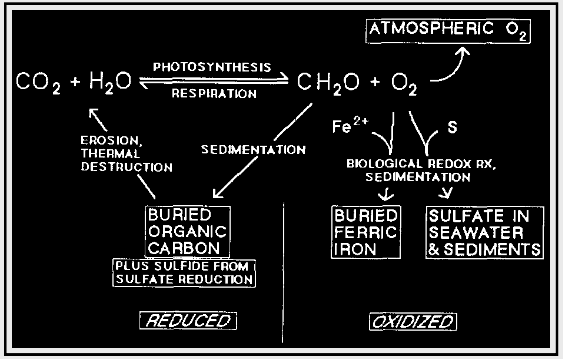




Cyanobacterial O production
🡐 and oC-Sd sequestration
Des Marais (1994)

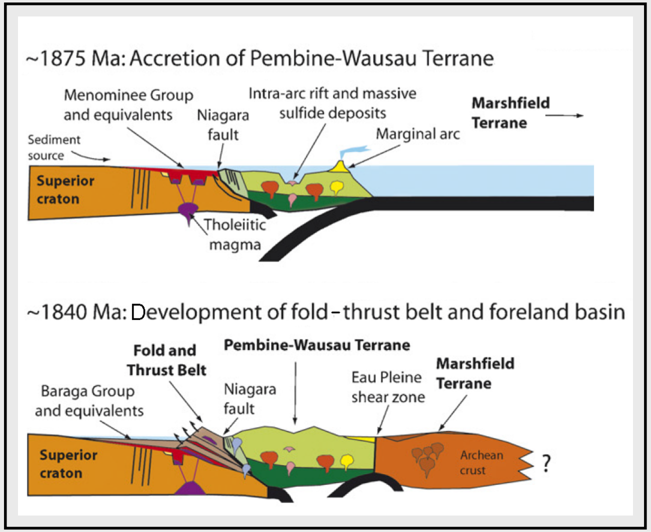
C-S concentration in starved basins
Sandberg and Gutschick (1983)



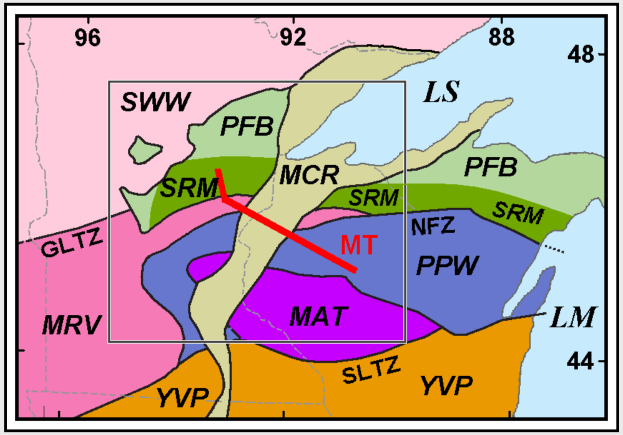

oC-Sd global primary production



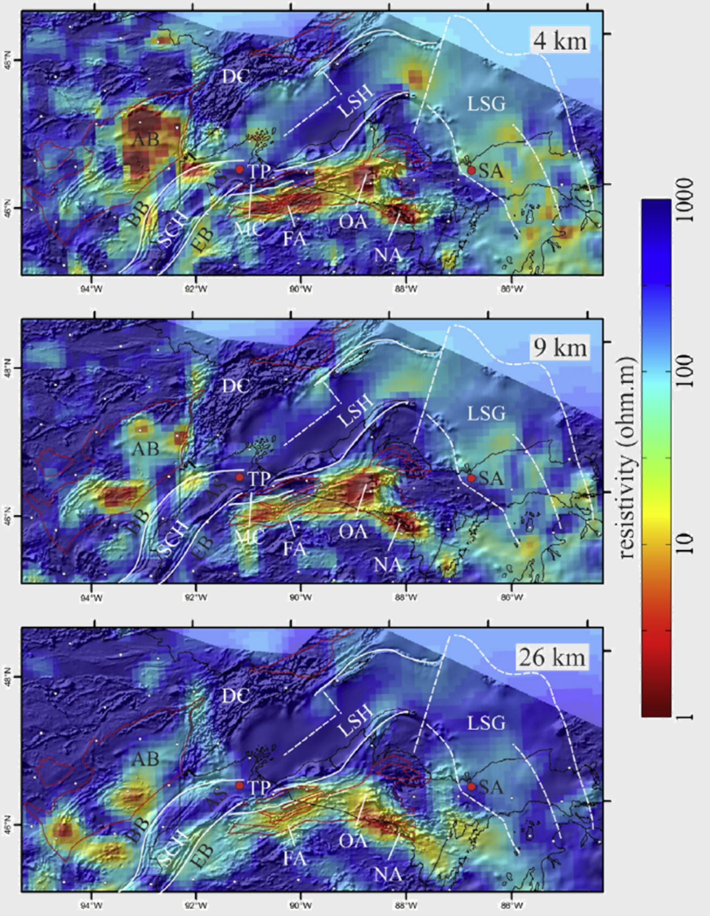

oC-Sd sequestration



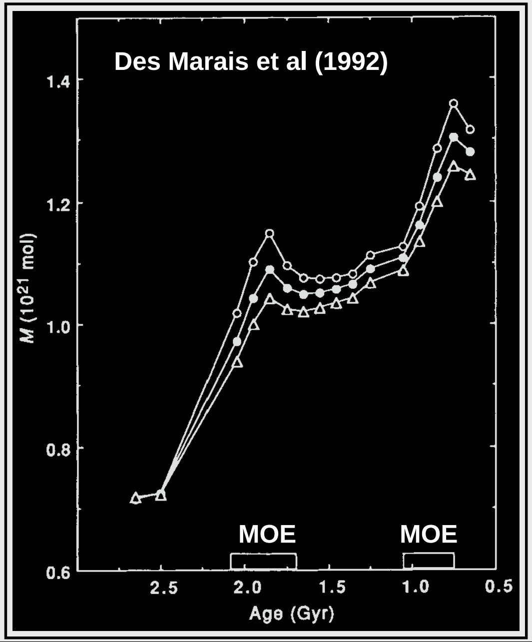

Mod from Schulz and Cannon (2007)



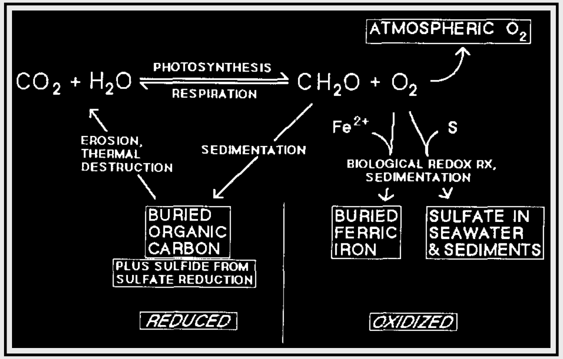

Mod from Southwick (2014)



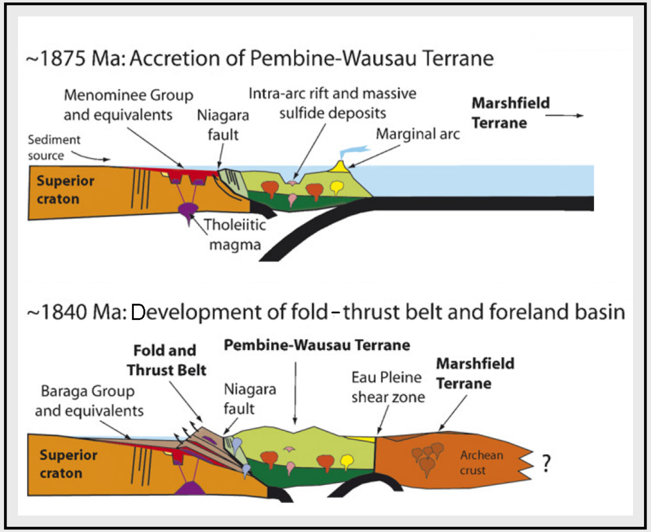

Bedrosian (2016)




oC-Sd global primary production




oC-Sd sequestration

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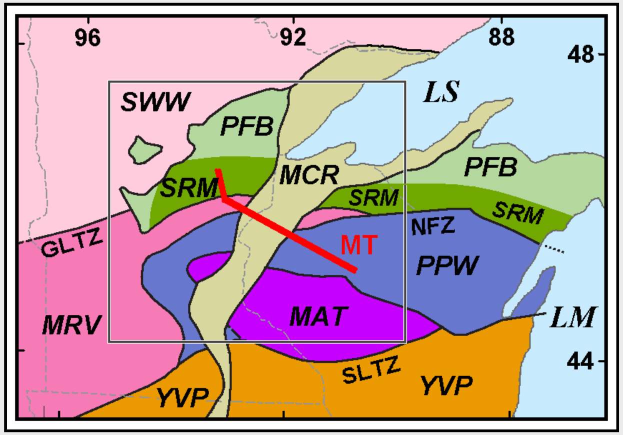
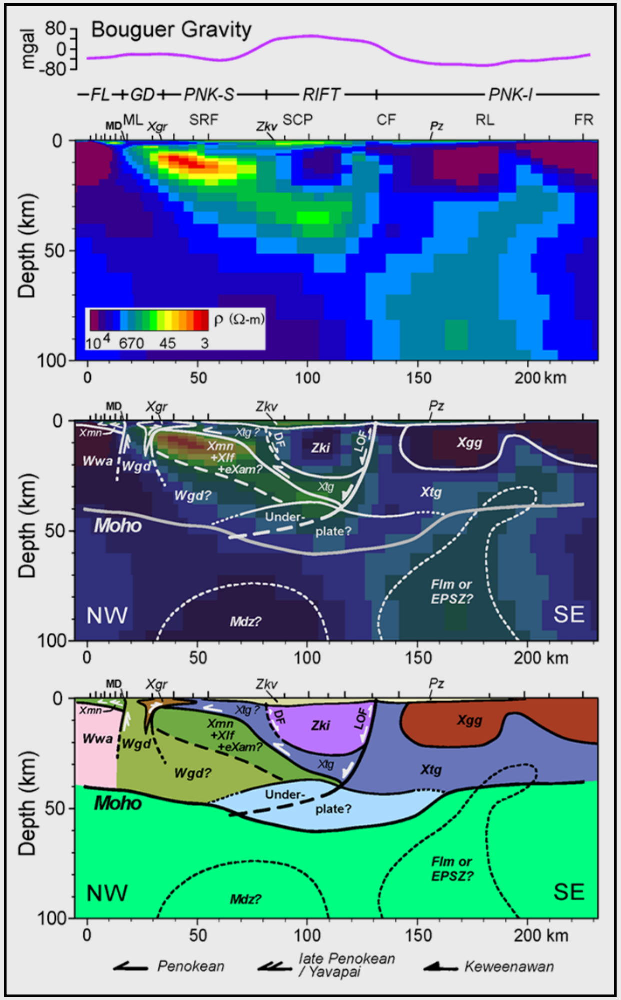
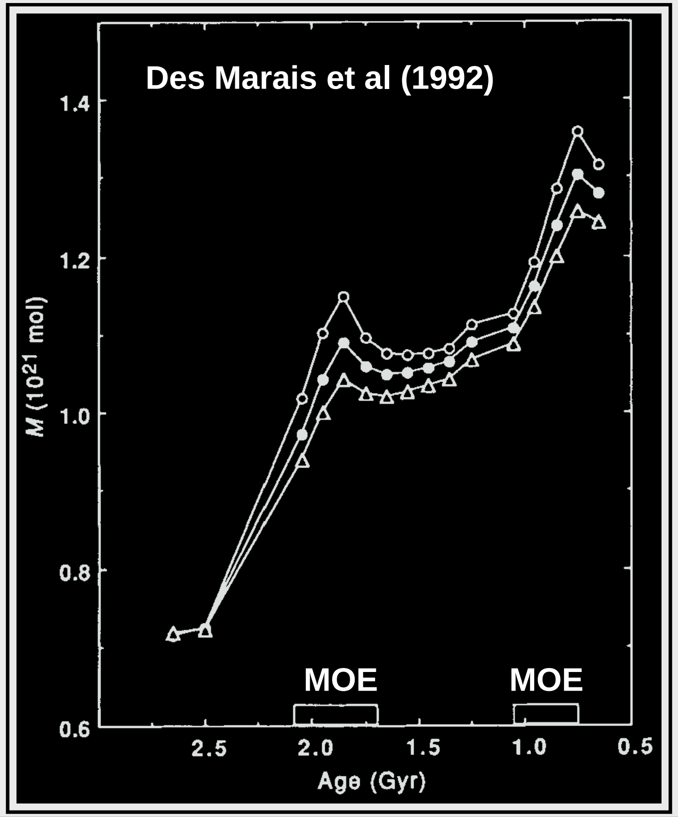


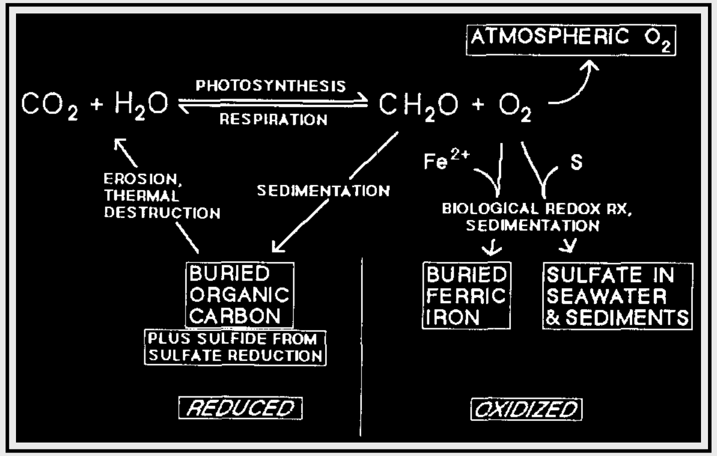

Mod from Southwick (2014)



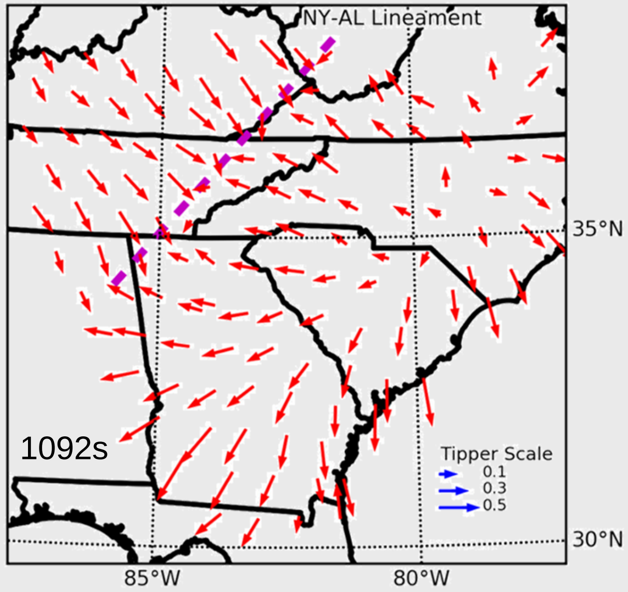

Wunderman et al. (2018)



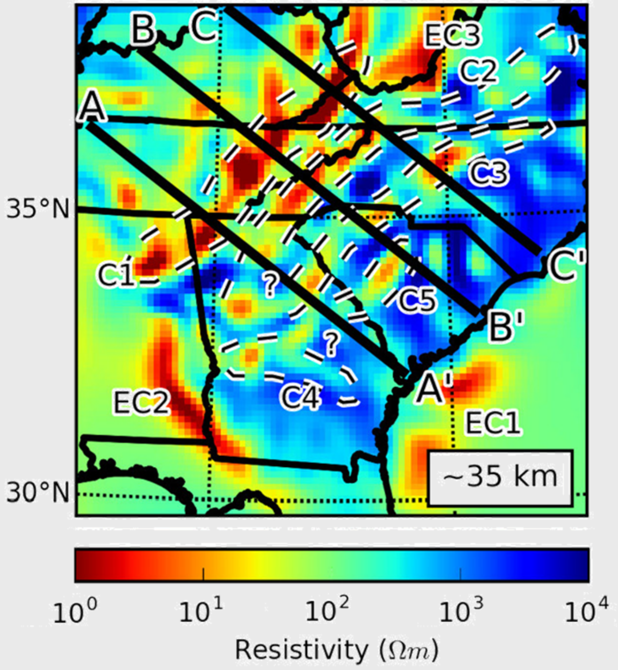

oC-Sd global primary production

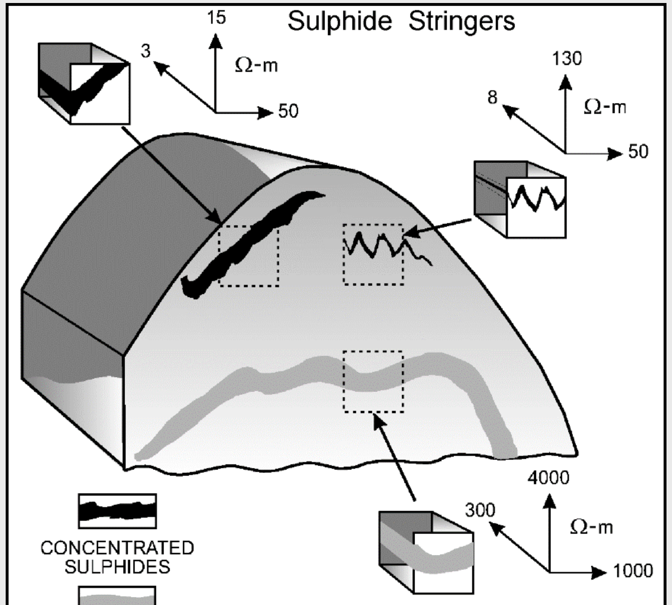



oC-Sd sequestration

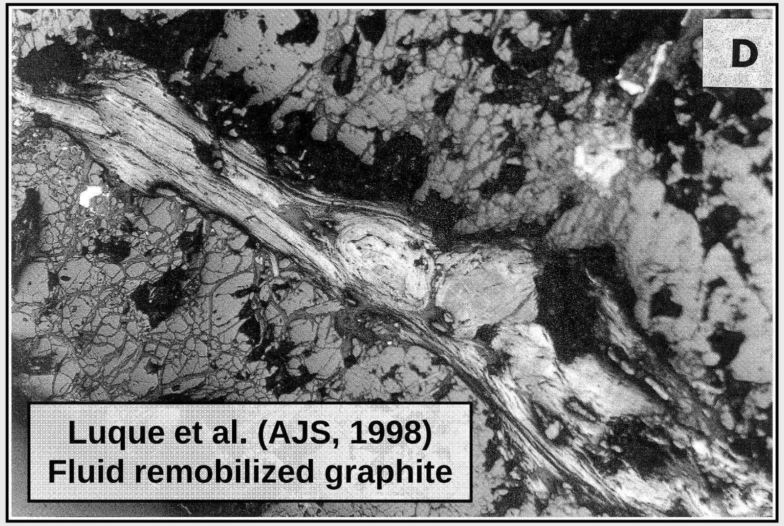



Murphy and Egbert (2017)




**Jones et al. (JGG,1997)**
**Sulfide Stringers**

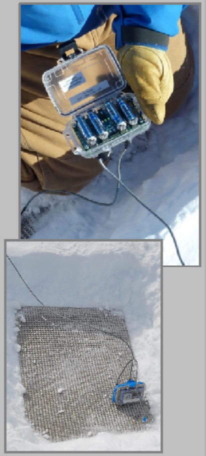



**Luque et al. (AJS, 1998)**
**Fluid remobilized graphite**

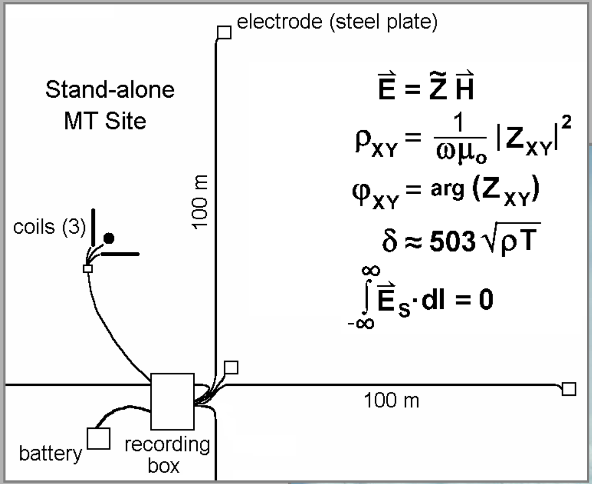
**Graphite-sulfide textures in crustal-scale conductors**

# MT Recording Components For Polar Deployment

Induction Coil (Solenoid)



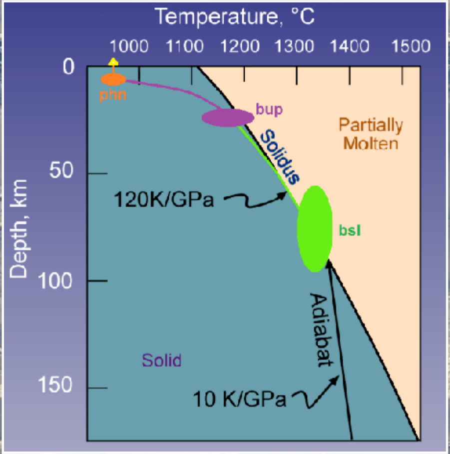
Ti Electrode w/ High-Z Preamp

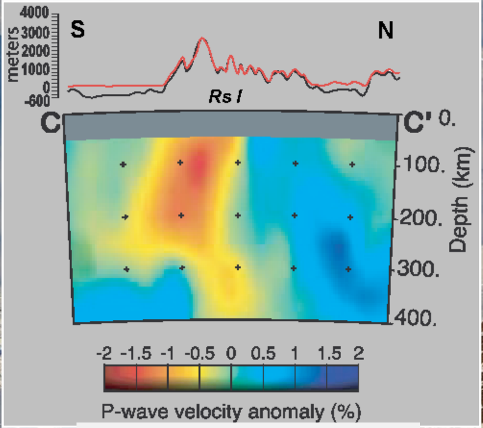




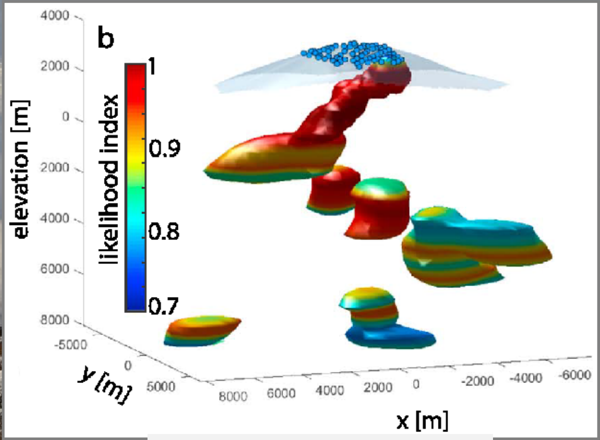
Sync'd MT recorders

Mount Erebus, Ross Island
(G. Hill, P. Wannamaker)

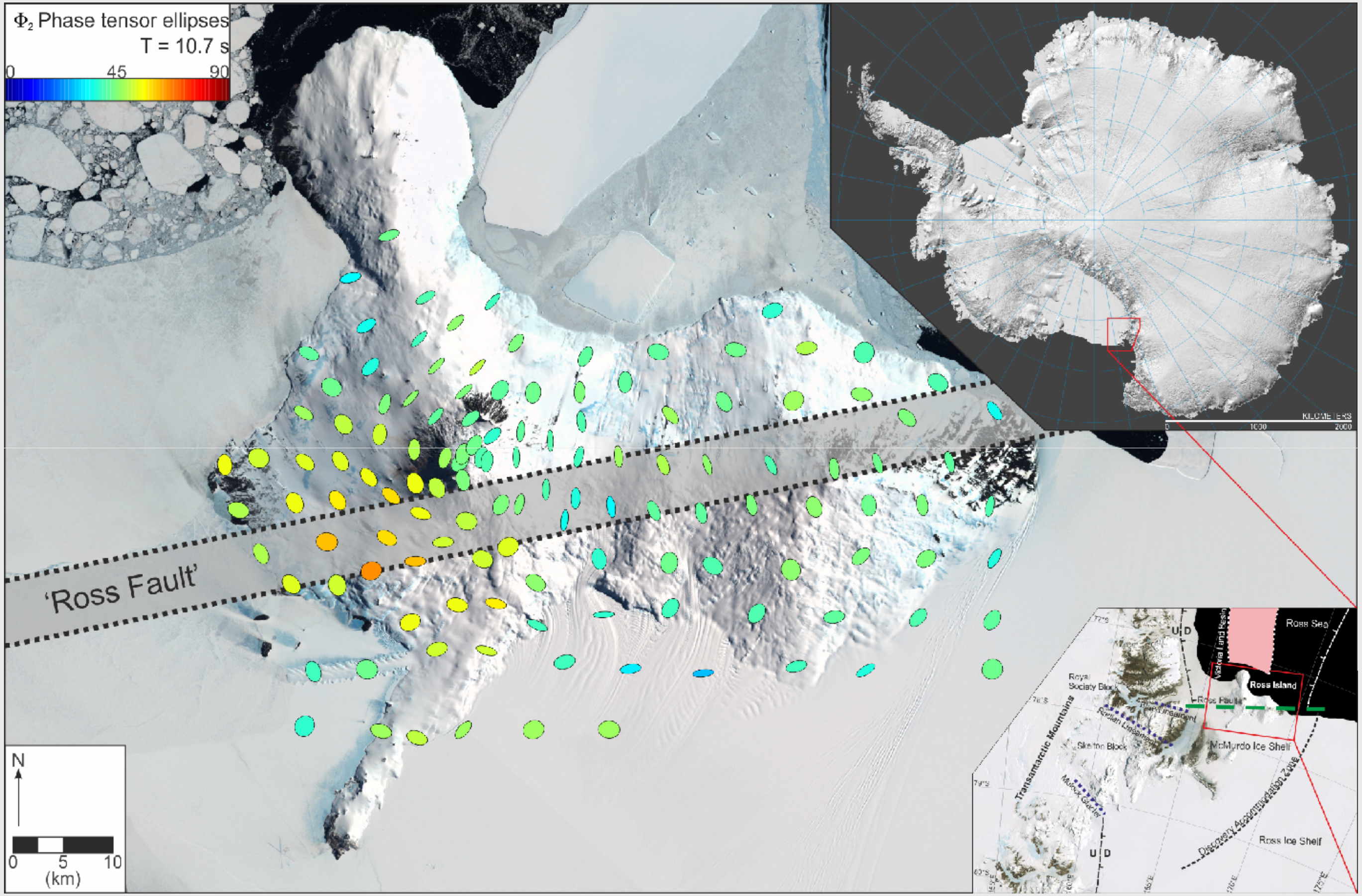


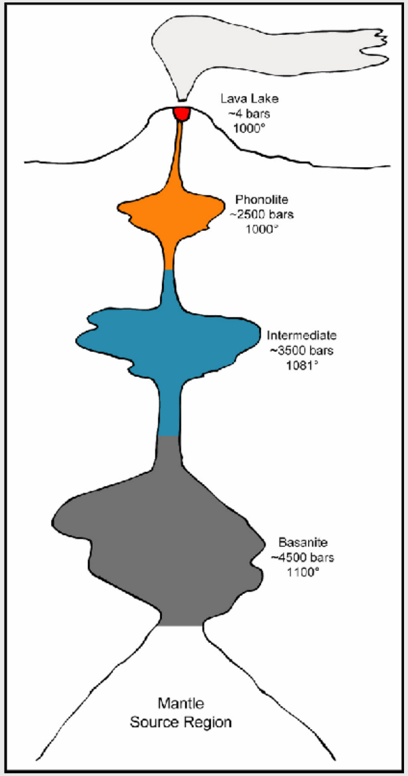




Watson et al (2006)




Blondel et al (2018)

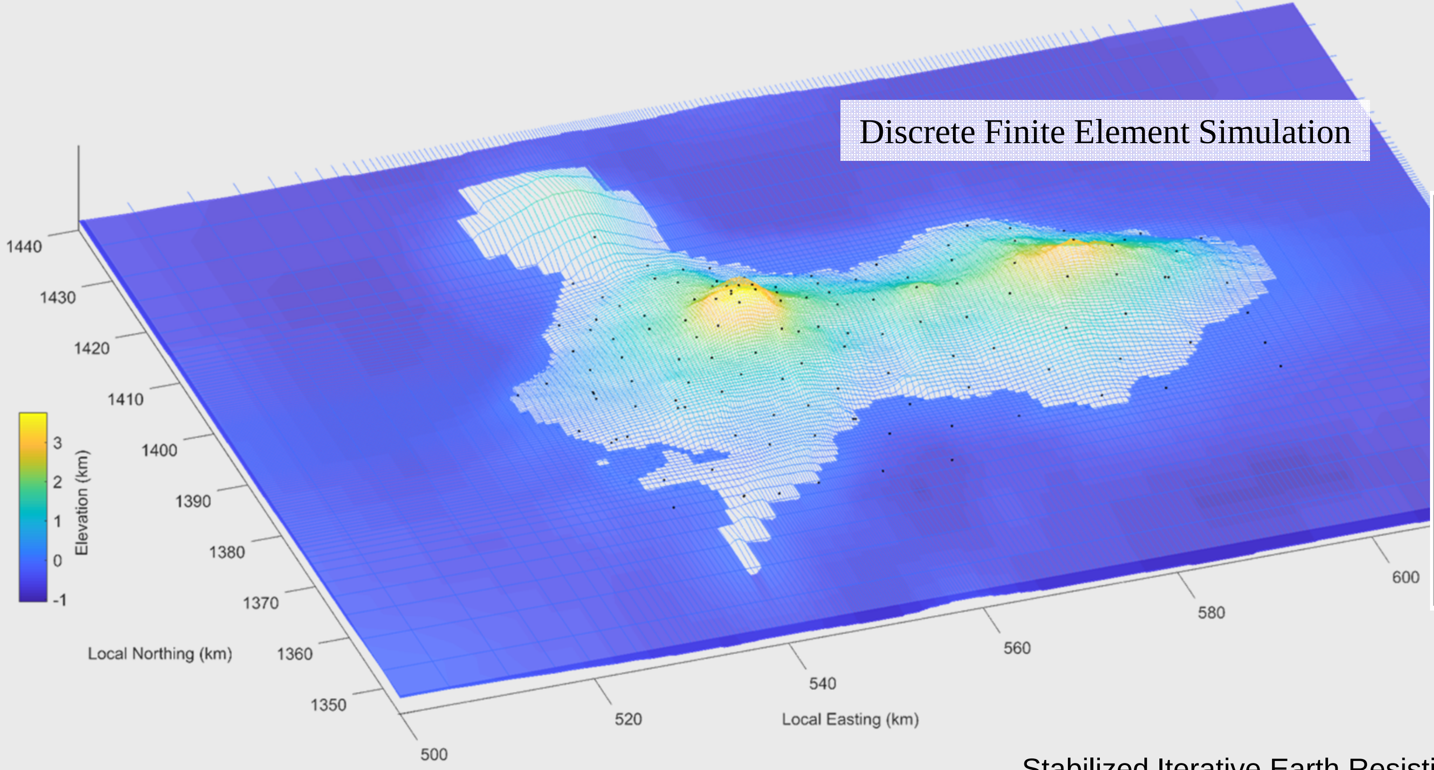



Mount Erebus Magma Source and Staging (Iacovino et al, 2015, after Oppenheimer, 2008)

# Mt Erebus MT Field Campaign: NSF/USAP and RSNZ/AntNZ

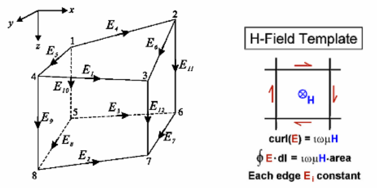
**Hill, Wannamaker, Maris, Stodt, Kordy, Wallin, Unsworth, Bedrosian, Uhlmann (2014-7)**




$$\nabla \times E = -i\omega\mu H \qquad \nabla \times H = \hat{\sigma} E$$

$$\nabla \times \frac{1}{\mu} \nabla \times E - i\omega\hat{\sigma} E = J^{imp}$$

$$E = \sum_{i=1}^{n_e} x_i N_i \qquad H = \frac{-\nabla \times E}{i\omega}$$



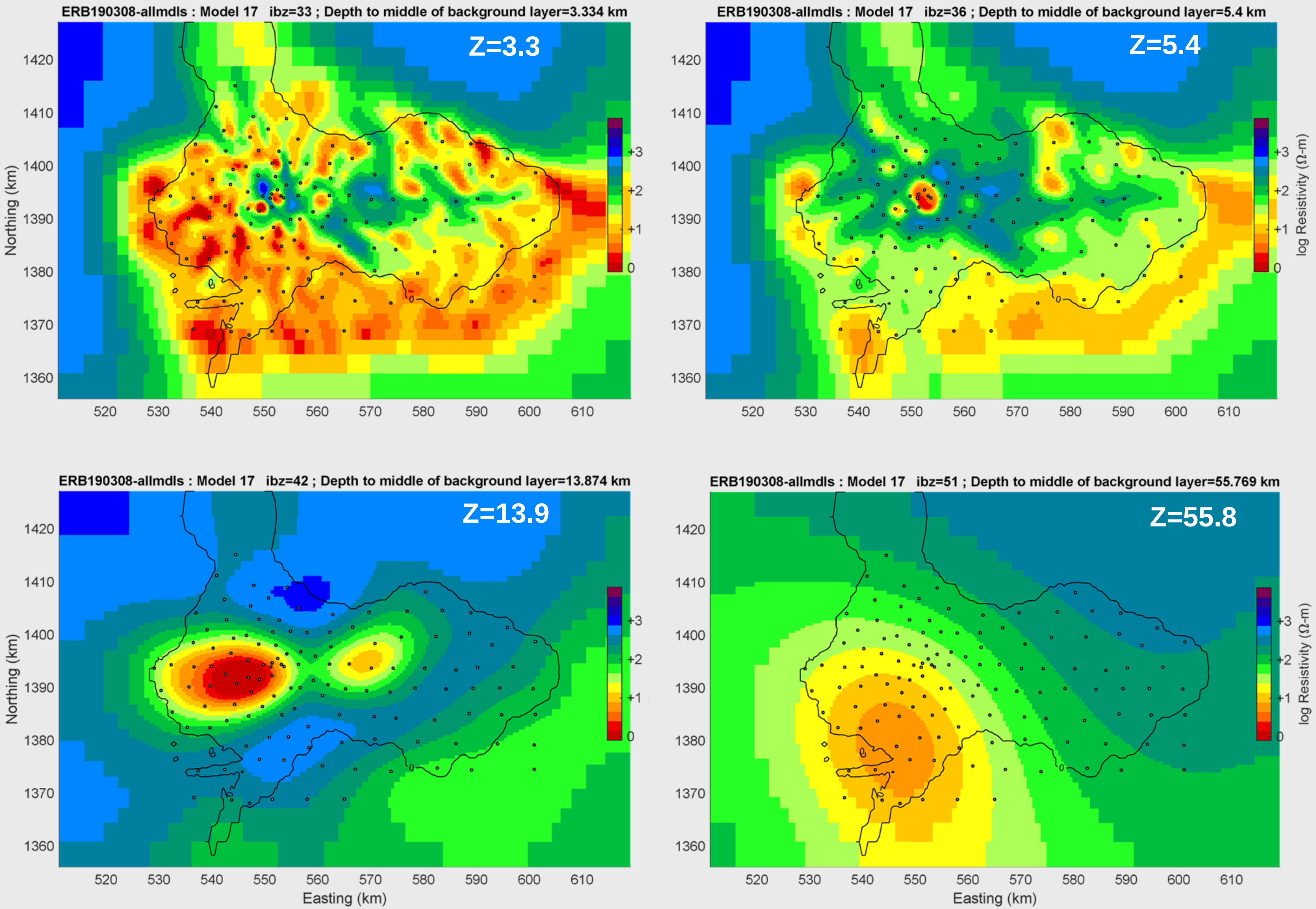

***EM Field (Maxwell) Equations***
***And Deformed Finite Element***

Objective: $W_\lambda(m) = \{(d - F[m])^T C_d^{-1}(d - F[m])\} + \lambda\{(m - m_o)^T C_m^{-1}(m - m_o)\}$

NL Step: $m_{k+1} - m_k = \{J_k^T C_d^{-1} J_k + \lambda C_m^{-1}\}^{-1}\{J_k^T C_d^{-1}(d_k - F[m_k]) - \lambda C_m^{-1}(m_k - m_o)\}$

Stabilized Iterative Earth Resistivity Voxel Estim. (Tarantola, 1987)
NL Step Recast to Data-Space Formulation (Parker, 1994)
Can Invert for Impedance Static Distortions (Avdeeva et al., 2015)
Direct Matrix Solutions Used Throughout (Metis, Pardiso, Plasma)
Parallelized on Large RAM, Single-Box Workstations

**3D MT Inversion of Using Deformable Edge Finite Element Algorithm**
(Kordy, Wannamaker, et al., 2016, GJI)



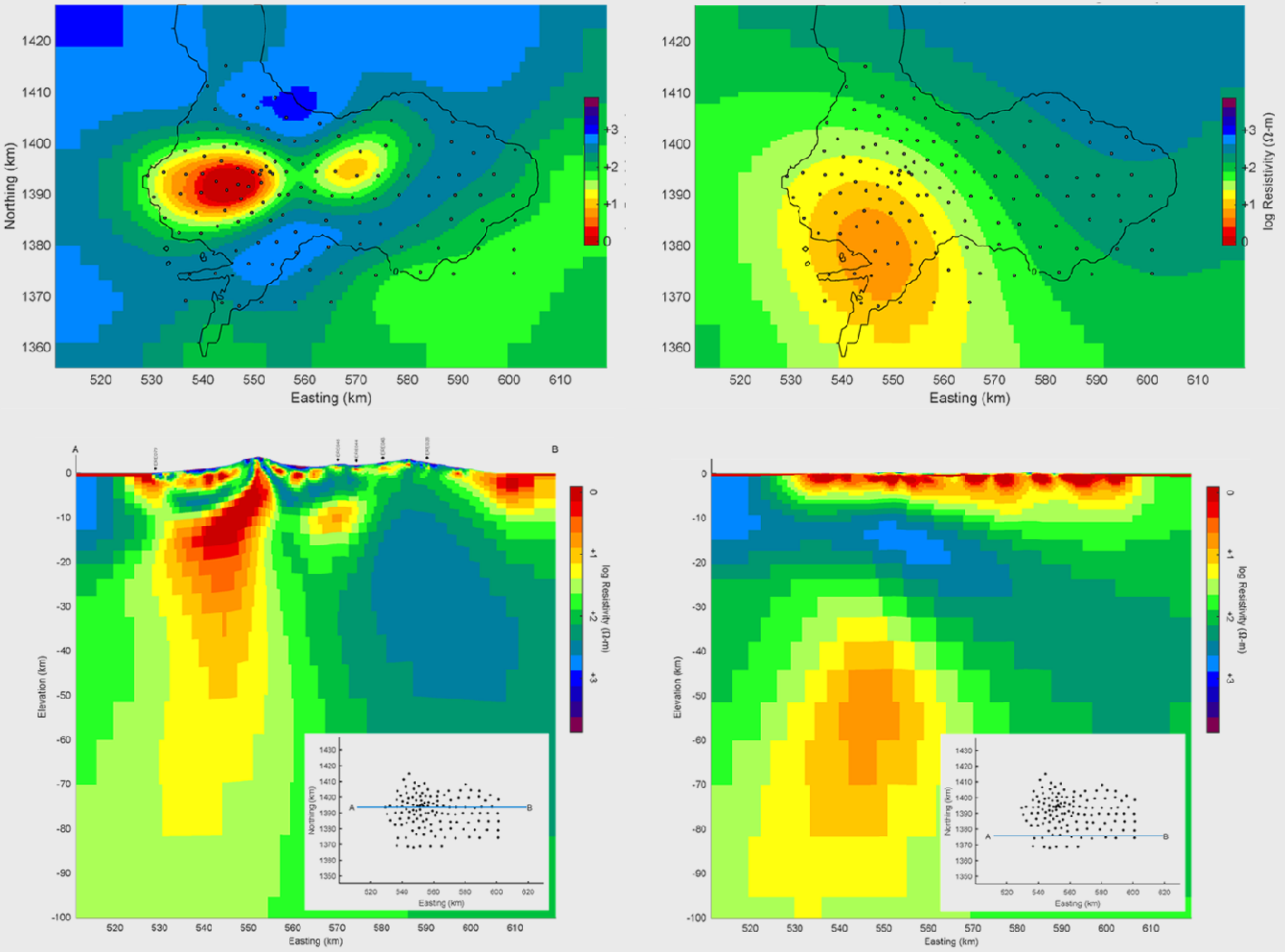

# Mount Erebus MT Inversion Resistivity Plan Sections:

- General clay alteration blanket at shallow levels.

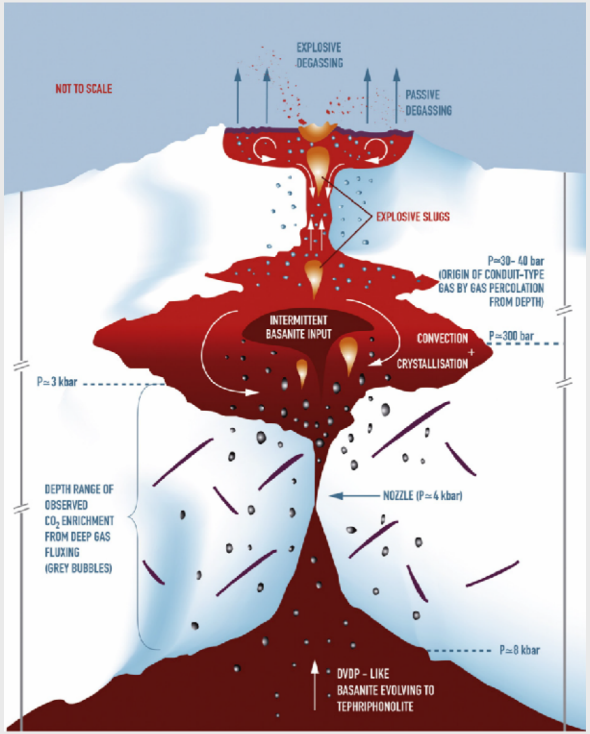
- Clear visibility of magmatic conduit and upper chamber by 5 km depth.

- migration of magmatic structure westward along apparent controlling E-W trend.

- Movement of magmatic plumbing southward from lower middle crust and deeper.




Mount Erebus MT Inversion Plan and Section Views




Schematic Mount Erebus magmatic plumbing (Oppenheimer et al., 2008). Note “Nozzle” interpreted at 4 kbar for periodic basanite replenishment.

<u>Conclusions and Outlook:</u>

- Key elements of MT method in t/s processing and in recognizing heterogeneity developed in 1970s & 80s
- 1990s saw methods for stable modeling of discontinuous E-field
- Current inversion algorithms capable of 1000+ sounding sets
- Proper understanding of petrological principles needed for consistent interpretation and to advance beyond “It’s fluids”
- External constraints on temperature most useful
- Active Great Basin extensional regime seems to exhibit “banana-split” model of crustal rheology
- Potential to evaluate geothermal resources for baseload power
- Wide-scale Juan de Fuca-Gorda hydration of upper mantle
- Carbonized horizons may assist resolving terrane assembly
- Encourage progress in understanding physico-chemical controls on earth material resistivity

# The End!