Integrating Magnetotellurics, Soil Gas Geochemistry and Structural Analysis to Identify Hidden, High-Enthalpy, Extensional Geothermal Systems

Project Officer: Michael Weathers; Total Project Funding: $770,169

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Track 1: Hydrothermal

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Co-I's: B. Mack Kennedy (LBNL); James Faulds (U NV Reno); Joseph Moore (U UT/EGI)

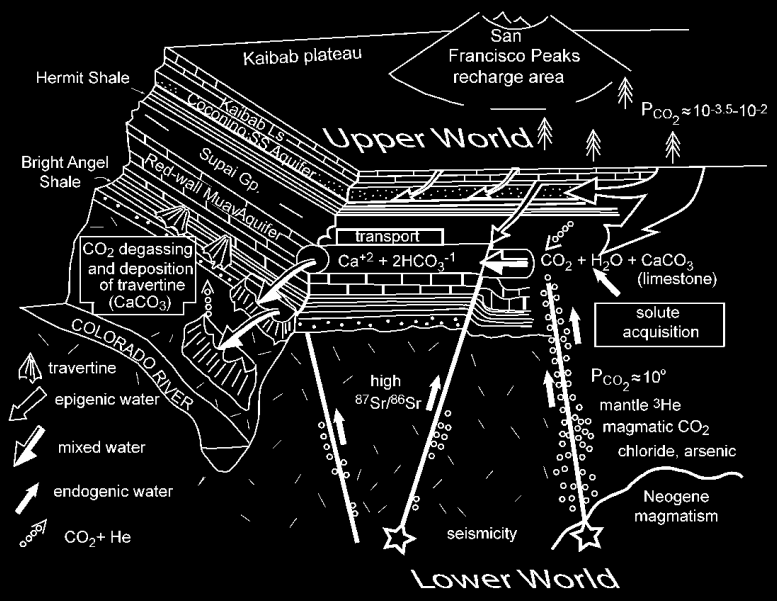
Relevance to Industry Needs and GTO Objectives

- Principal Objective: Accelerate Near-Term Hydrothermal Growth
  - Lower risks and costs of development and exploration
  - Lower levelized cost of electricity (LCOE) to 6 cents/kWh by 2020
  - Accelerate development of 30 GWe undiscovered hydrothermal resources

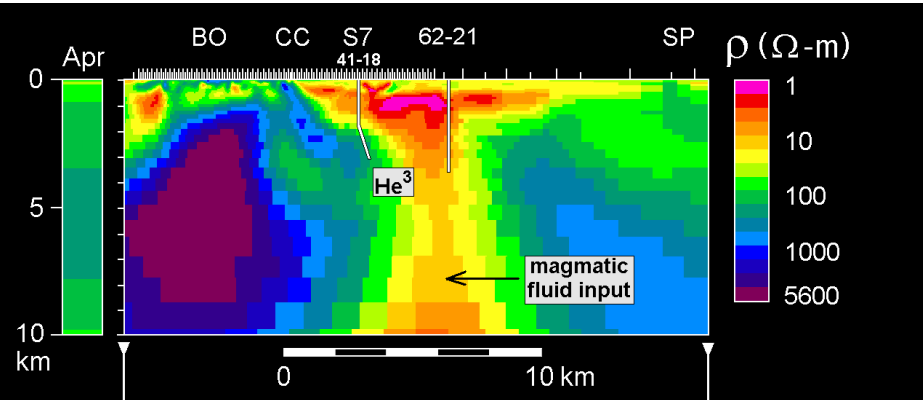
- *Challenges/Knowledge Gaps*: Many small, low-T systems but few large magnitude producers. Difficulty in establishing ultimate heat source. Non-uniqueness in the interpretation of individual techniques.
- *Cost Impact*: Improved recognition of high-T heat sources. Reduction of false structures and anomalies. Economies of scale and increased resource base.
- *Innovative Aspects*: Exploits recently-recognized opportunities in individual techniques. Combines highly independent methodologies to curtail non-uniqueness. Brings district-scale geophysical concepts into exploration. Strong cooperation with geothermal industry.
- *Meeting GTO goals*: Improves the process of identifying geothermal resources.

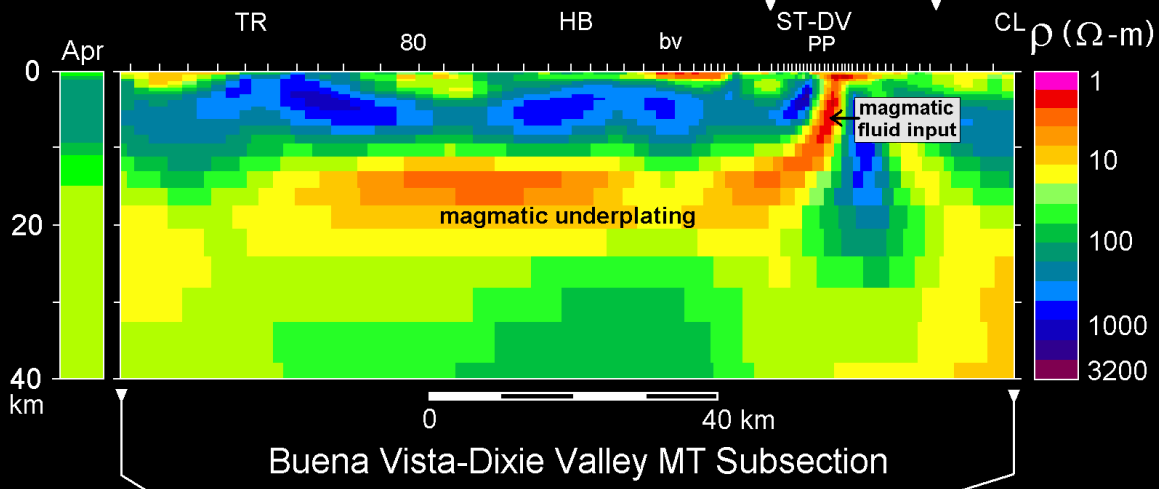
Defining High-T, High-Enthalpy Geothermal Systems

- 1), Select two districts in Great Basin with pronounced crustal-scale, low-resistivity upwellings (2-D) for large, high-T resource promise.
- 2), First is new development with proven resource (McGinness Hills, Ormat Inc.), favorable geophysical structure (Phase I).
- 3), Follow up with: a), 3D MT survey and inversion to pinpoint core structures, relation to production; b), detailed structural analysis with integration of industry data to resolve crustal fluid plumbing framework; c), Verify magmatic/deep metamorphic character of source using isotope geochemistry from soil gas and well surveying.
- 4), Presuming favorable confluence of geoscientific indicators, apply exploration concept to a more 'greenfield area': Black Rock/Kumiva Valley area (Phase II).
- 5), Scientific Team: Phil Wannamaker (P.I.), (U Utah)- Concept identification, 3D MT survey design and inversion; Jim Faulds (Co-I) (U NV Reno), - Structural controls on geothermal systems, new mapping and visualization; B. Mack Kennedy (Co-I) (LBNL), Isotope techniques in geothermal systems, noble gases and radiometric dating, crustal and geothermal fluid fluxes.



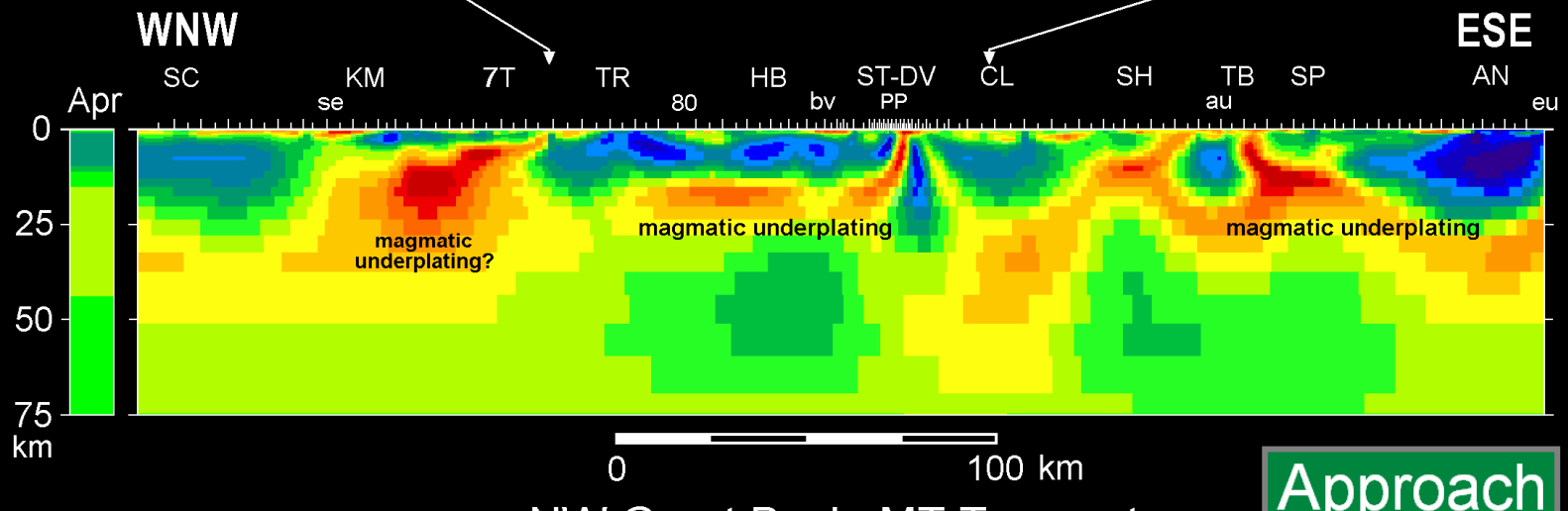
Grand Canyon Hydrol. Model
(Crossey et al., 2006)





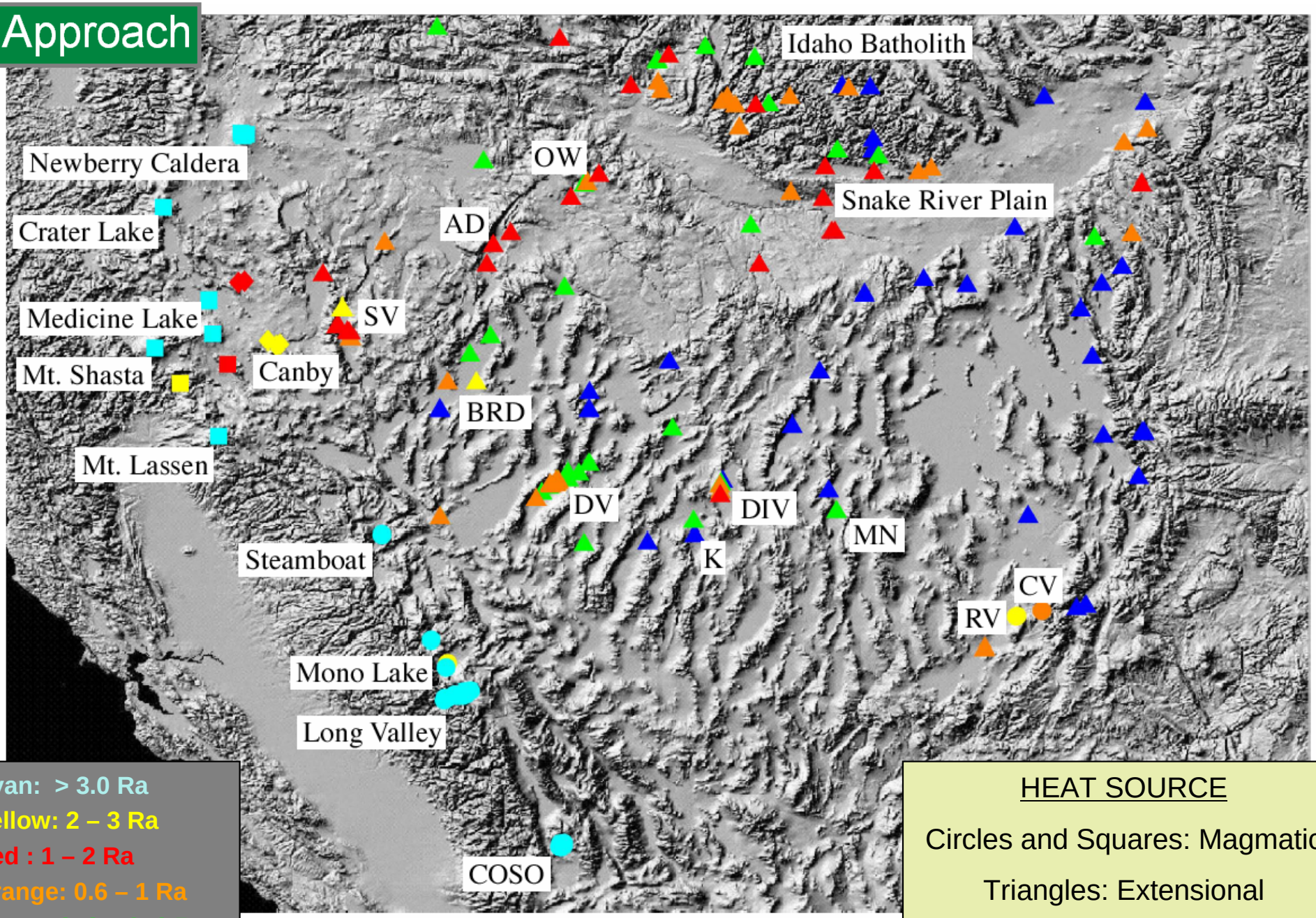
Multiscale Magmatic/ Hydrothermal Connections

(Wannamaker et al, 2007, 2013; Siler et al., 2014, GRC, SGP)



Approach

Approach



Cyan: > 3.0 Ra
Yellow: 2 – 3 Ra
Red : 1 – 2 Ra
Orange: 0.6 – 1 Ra
Green: 0. 3 – 0. 6 Ra
Blue: < 0.3 Ra

HEAT SOURCE

Circles and Squares: Magmatic

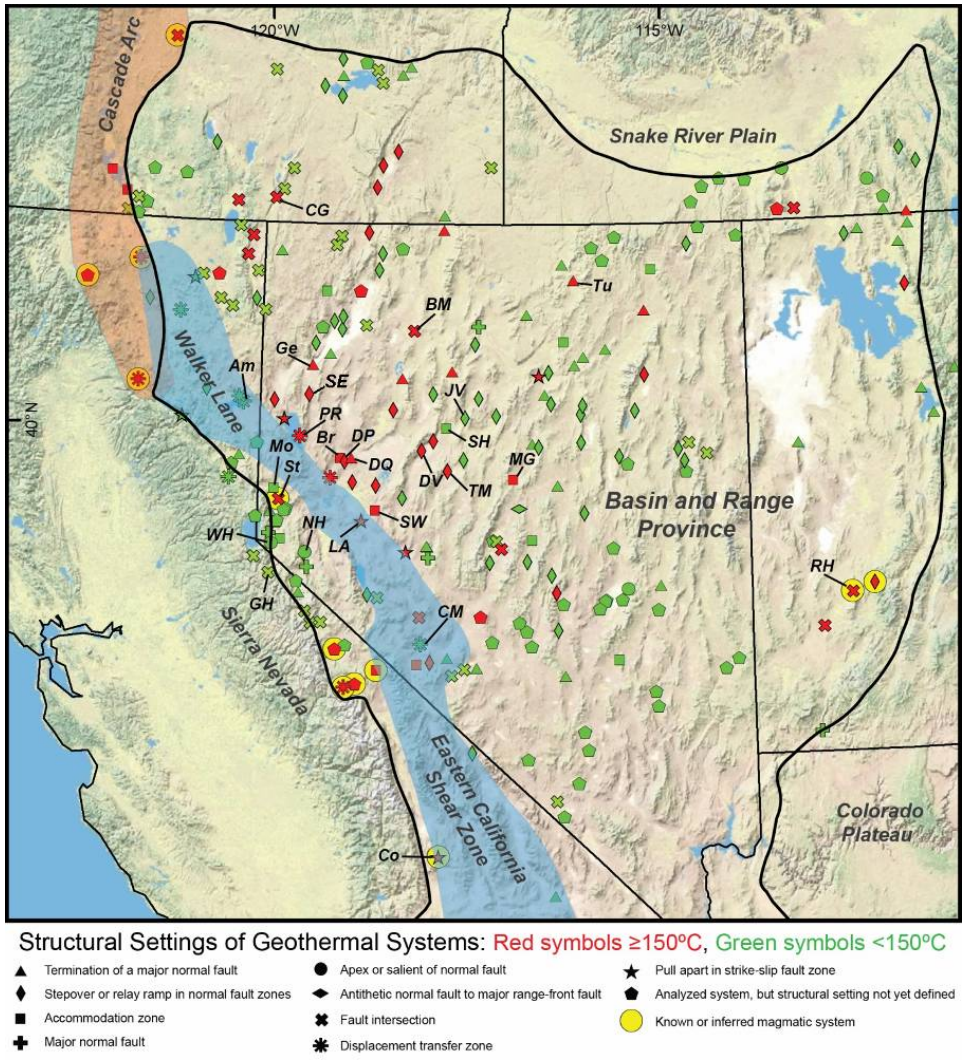
Triangles: Extensional

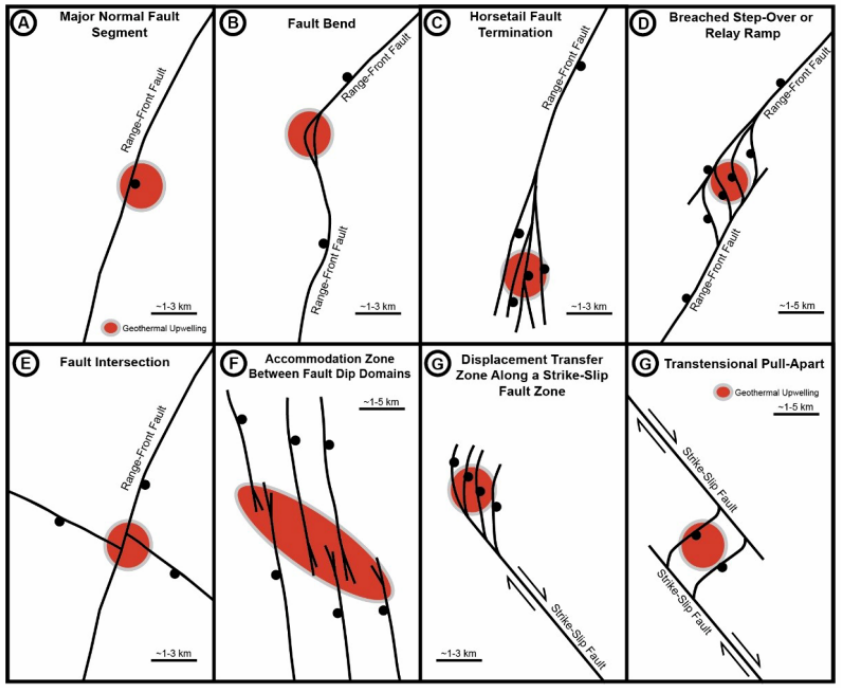
Diamonds: not sure

Mantle Helium Evidence

(Kennedy and van Soest, 2007, Science)

Scientific/Technical Approach





Favorable structural settings and setting types for geothermal systems (Faulds et al., 2015, WGC)

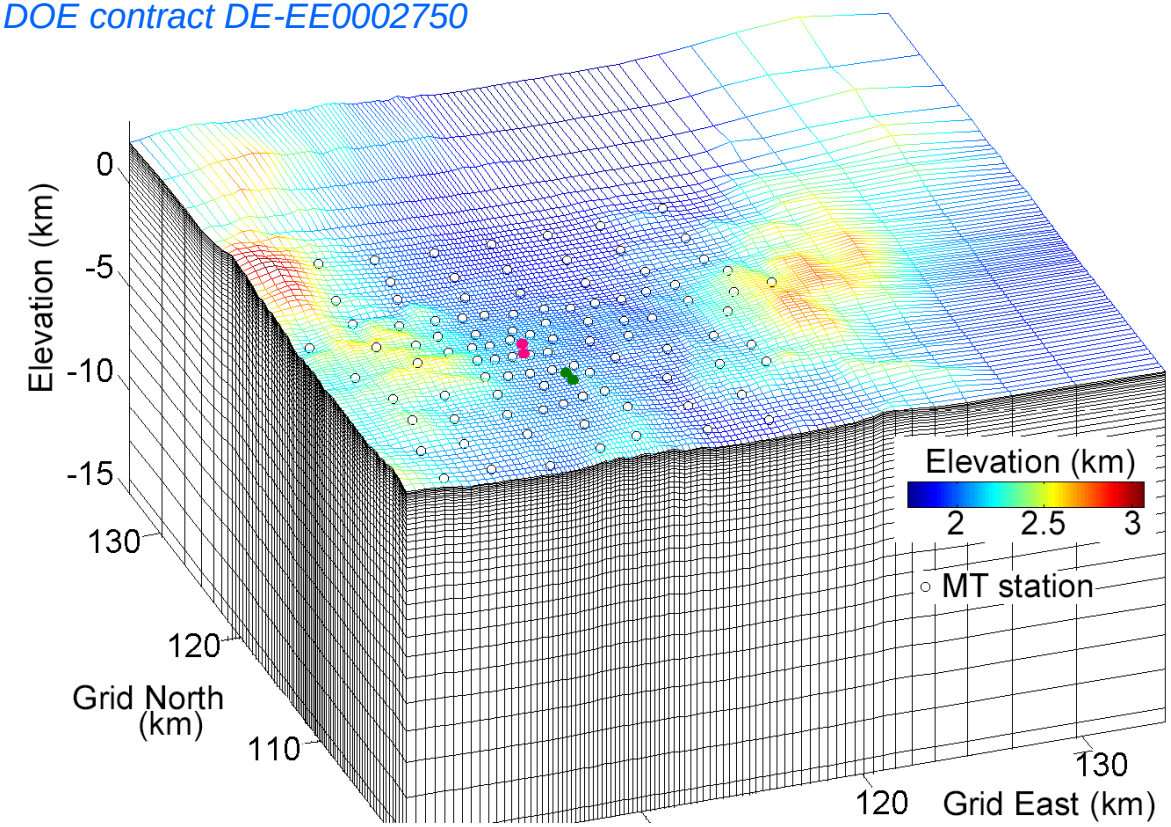
Technical Accomplishments and Progress

- McGinness Hills: 3D MT analysis confirms crustal scale permeable zone feeding in from east-southeast.
- Production in graben setting formed in accommodation zone. Anomalous 3He, CO2 flux with 13C present.
- Kumiva Valley: 3D MT confirmation of low resistivity crustal upwellings, but relatively diffuse.
- Numerous Q fault scarps, favorable 3D structures north end of Granite Springs Valley.
- Passive CO2 soil gas flux readings subdued; minor anomalies Seven Troughs flanks, east Kumiva Valley.

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
1a. 3D MT surveying of McGinness Hills and 3D inversion model	Achieved Original	Nov. 2013
2a. In-field mapping and structural analysis of McGinness Hills augmenting Ormat	Achieved Original	Jun. 2013
3a. CO2 and 3He geochemical surveying at McGinness Hills, coop with Ormat	Achieved Original	Sep. 2014
Go/NoGo: McGinness Hills Geophysical-Geological-Geochemical Study Definitive	Go Affirmative	Oct. 2014
1b. 3D MT surveying of Kumiva Valley are and 3D inversion model	Achieved Original	Apr. 2015
2b. In-field mapping and structural analysis of Kumiva/Granite Springs Valley	Achieved Original	Jun. 2017
3b. CO2 flux surveying at Kumiva/Granite Springs Valley area	Achieved Original	Sep. 2017

U.S. DOE contract DE-EE0002750

Tech A & P



Advanced 3D MT Imaging

< Finite Element Mesh, 100 sites: McGinness Hills Geothermal System, Nevada

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

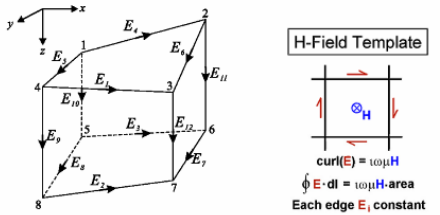
$$\text{NL Step:} \quad m_{k+1} - m_k = \{J_k^T C_d^{-1} J_k + \lambda C_m^{-1}\}^{-1}\{J_k^T C_d^{-1}(d_k - F[m_k]) - \lambda C_m^{-1}(m_k - m_o)\}$$

Stabilized Iterative Earth Resistivity Voxel Estimation
Non-Linear Model Step Recast to Data-Space Formulation
Direct Matrix Solutions Used Throughout (Pardiso, Plasma)
Can Solve for Tensor Impedance Static Distortions
Parallelized on Large RAM, Single-Box Workstations

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

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

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

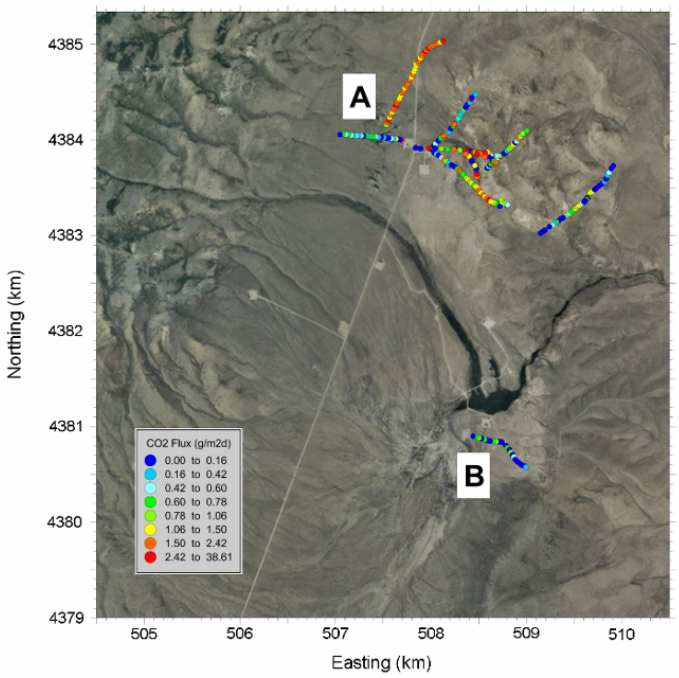


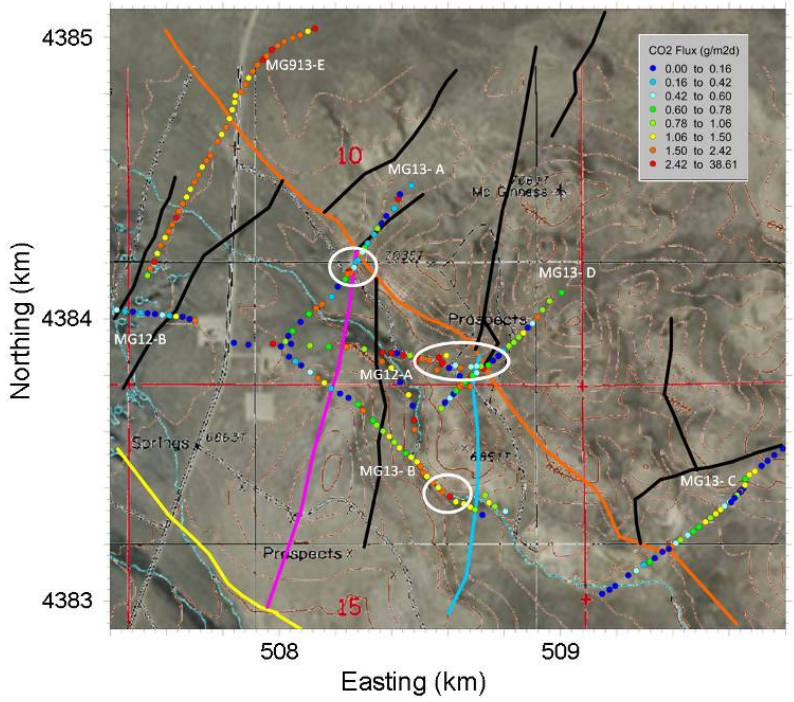
EM Field (Maxwell) Equations
And Deformed Finite Element

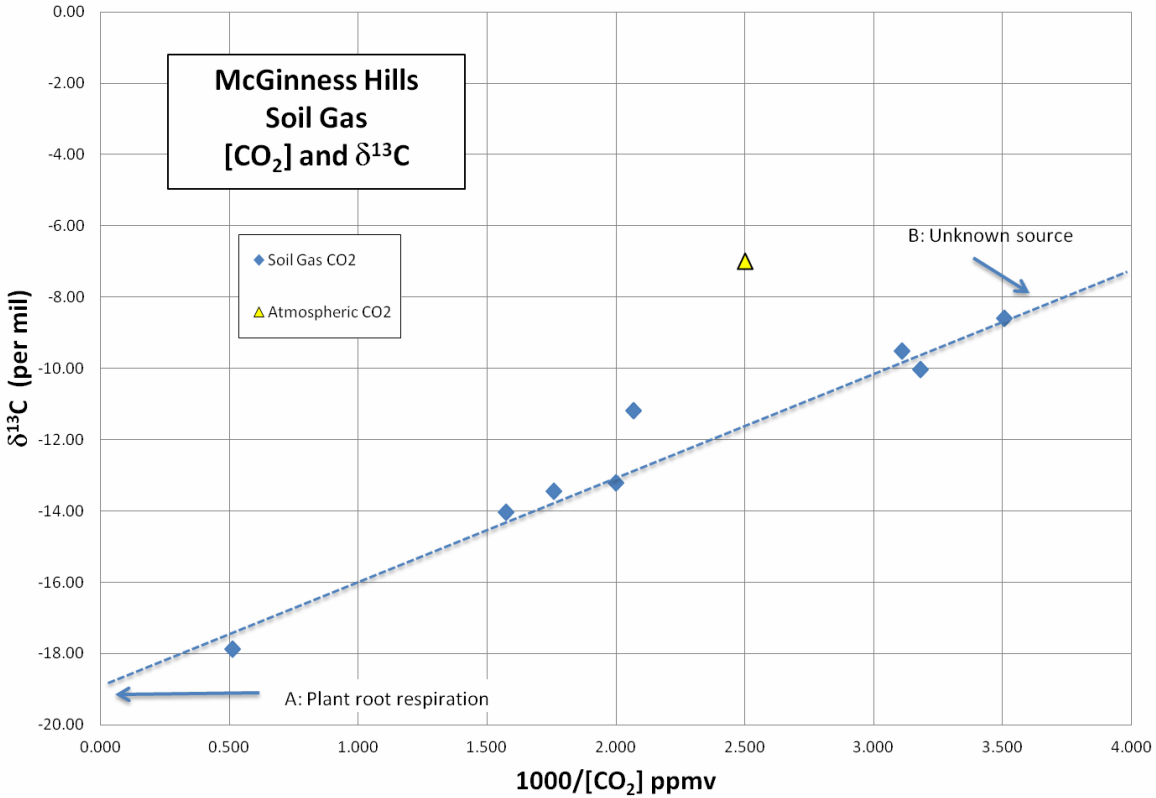
3D MT Inversion Using Deformable Edge Finite Element Algorithm
(Kordy, Wannamaker, et al., 2016, GJI)

Tech A & P

Soil CO_2 gas flux surveying



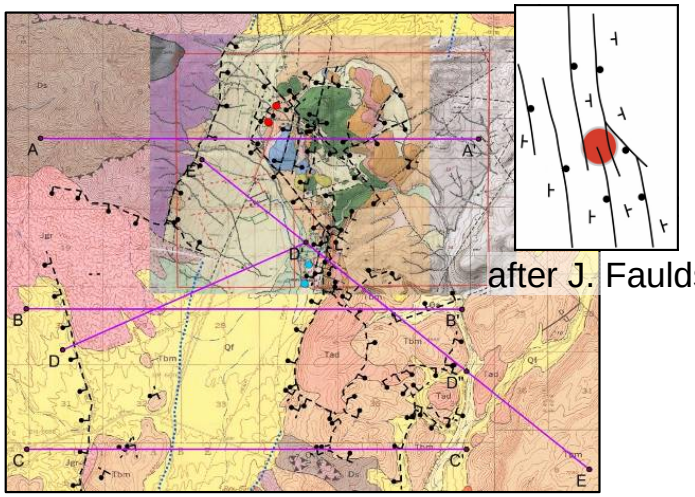




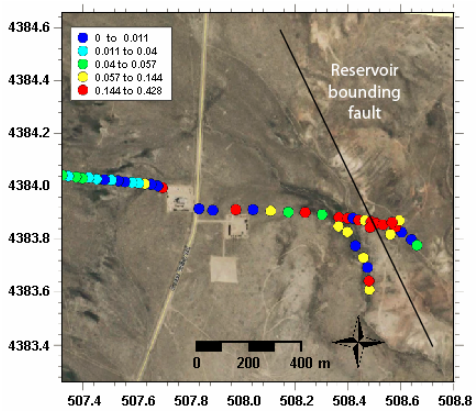
Possible metamorphic ^{13}C present in McGinness Hills System soil flux

McGinness Hills Geothermal System – Natural Lab for Deep Sources

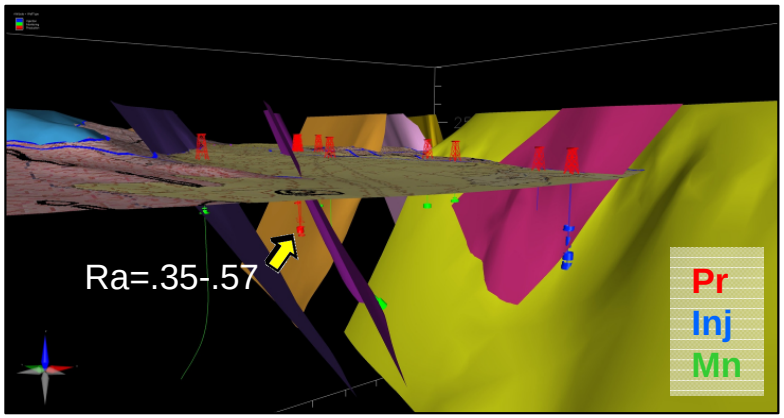
- Structural setting as accommodation zone
- Deep magmatic connection from elevated Ra
- CO_2 flux anom. along Nly NW fault zone (first data)

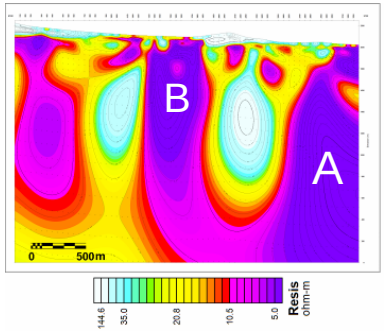


after J. Faulds



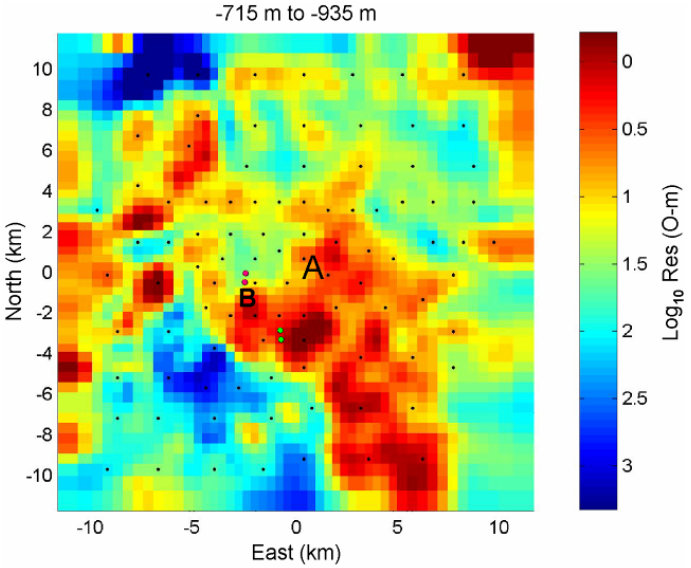
from B. M. Kennedy
('dead' ^{13}C confirmed)

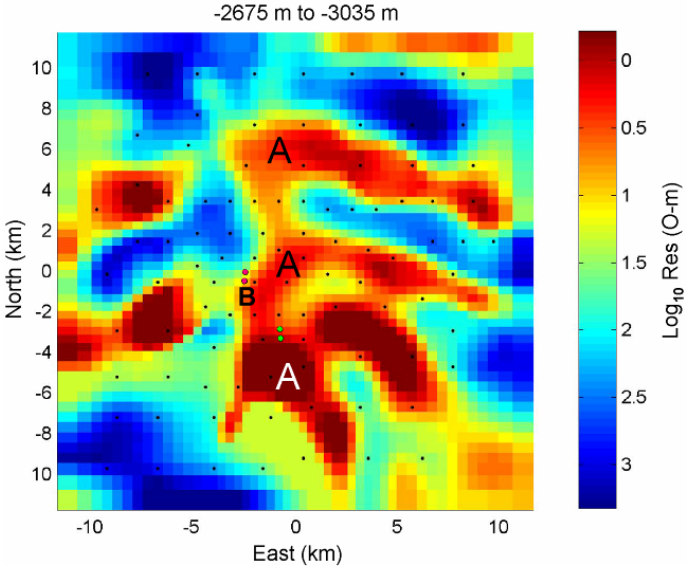




Dense MT Array Model

- 3D MT confirms 2D recon
- Connection of prod. to depth
- NW-SE trends at multi-scale





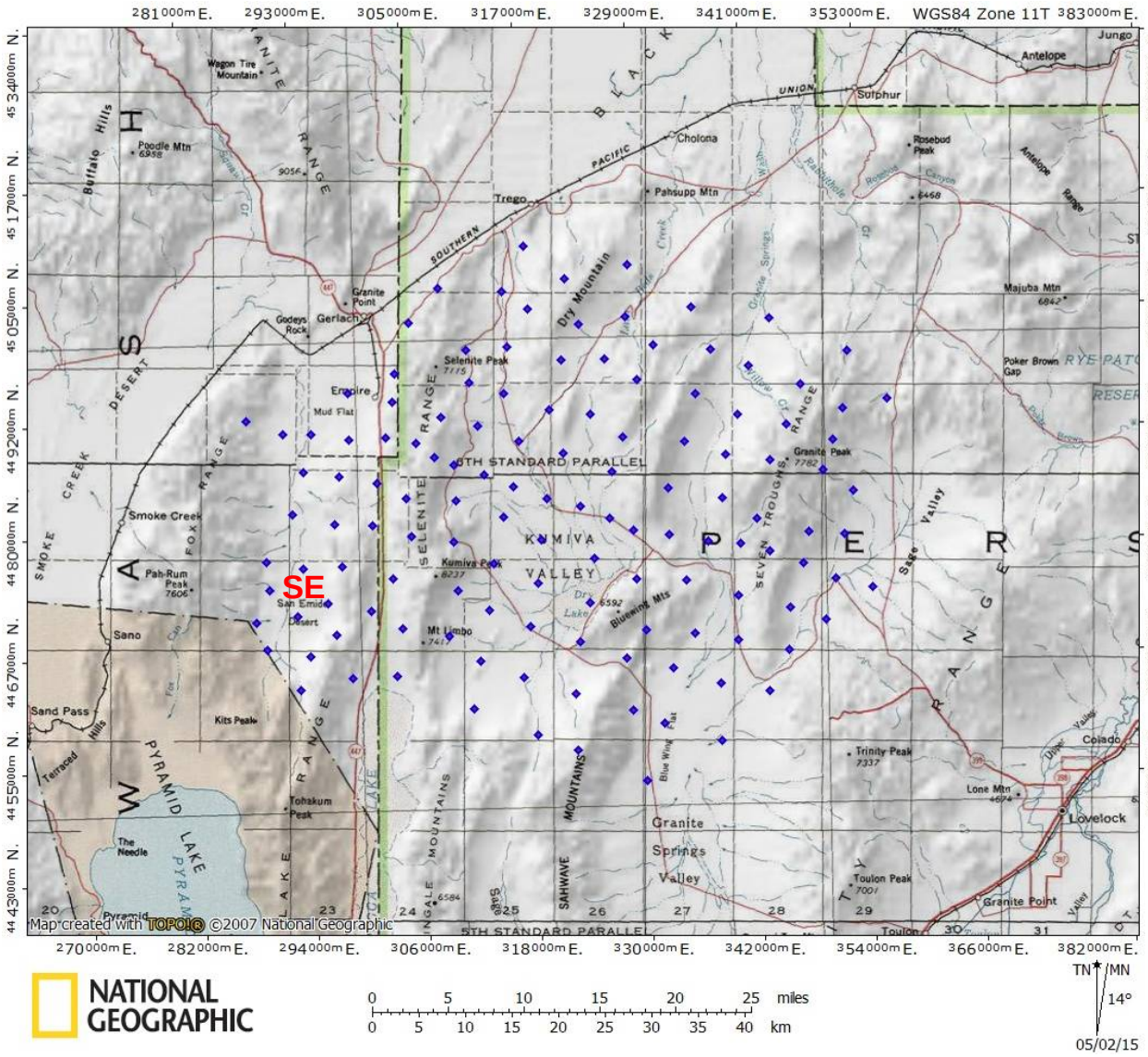
3D MT Resistivity Plan Views
B is production, A is deep regional

⇧ 3D structural perspective view from mapping and wells; high He Ra in production wells

⇦ Purging sample port on well 36-10 for He sampling (L. Owens, Ormat)

Tech A & P

Tech A & P



Kumiva Valley Area 3D MT Survey:

- Total of 105 stations including original transect soundings.
- DC line along Hwy 447 required 300 km distant remote reference (east of Midas, NV)

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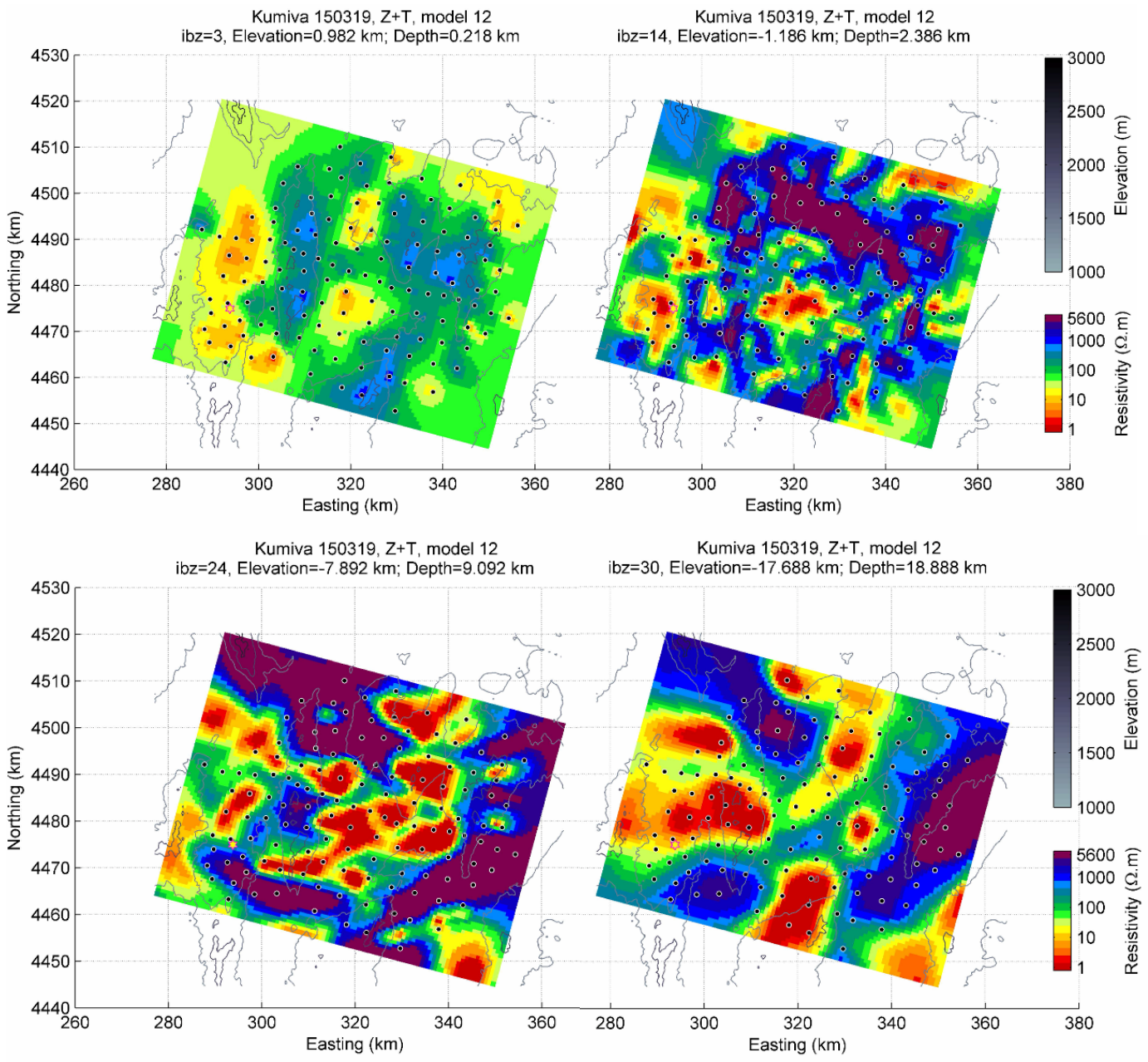
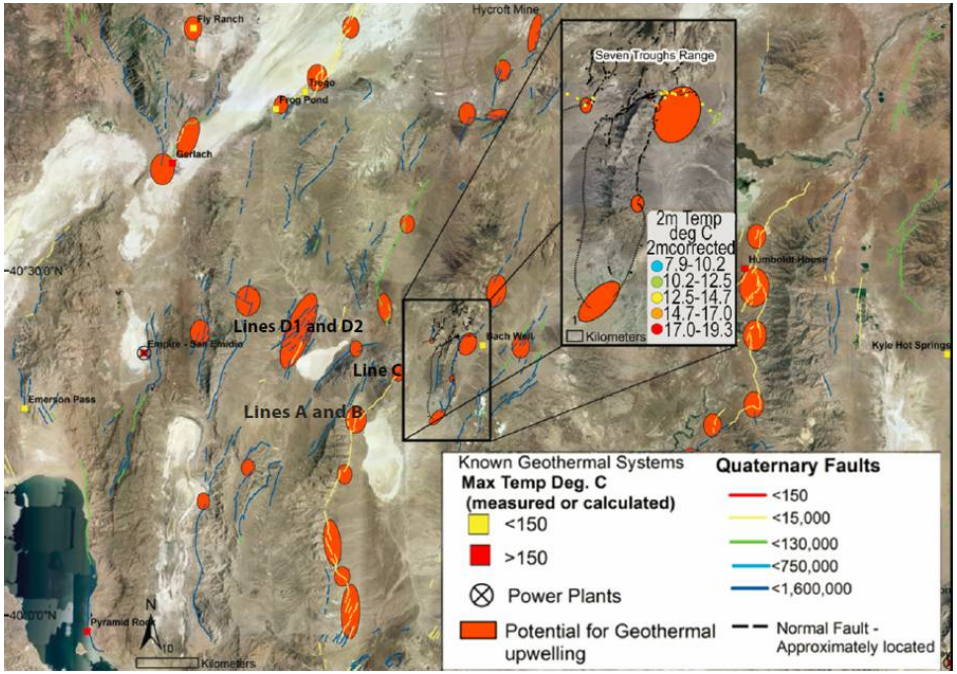
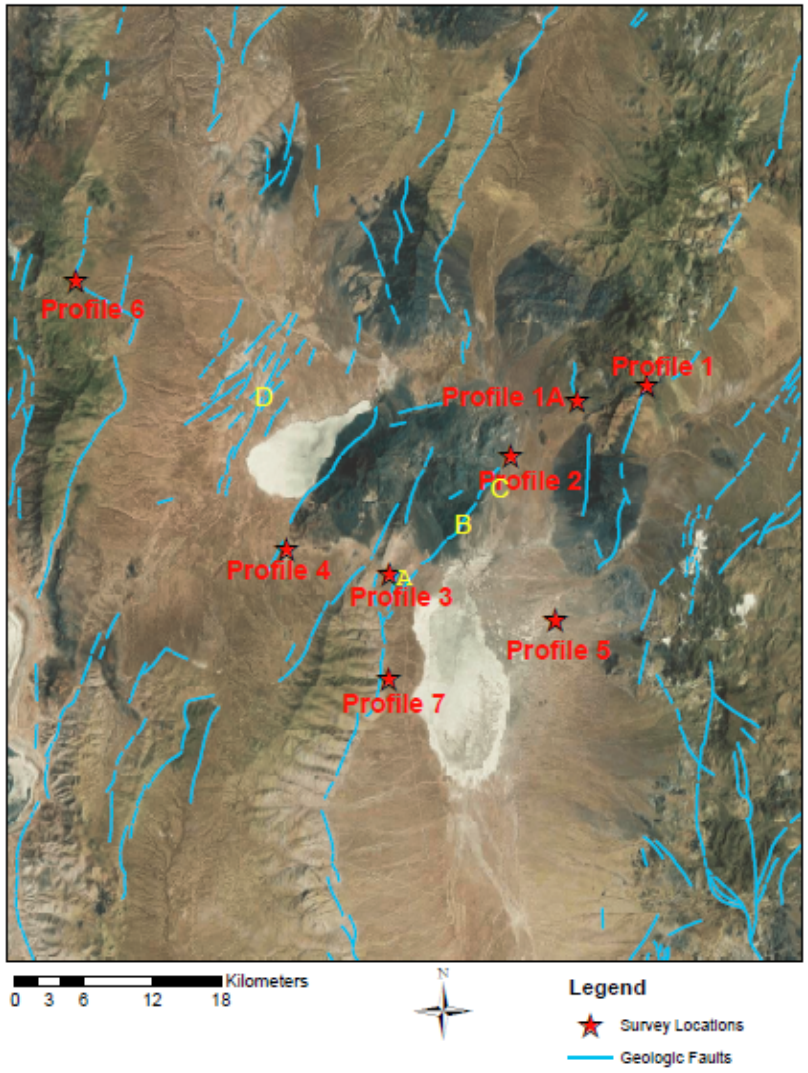


Kumiva Valley Area 3D MT Survey:

- Plan views at four depths through Kumiva region, complexly 3D. Star denotes San Emidio.
- Upwelliings west side of Blue Wing Mtns, north Granite Springs Valley to Seven Troughs Rg.

Technical Accomplishments and Progress

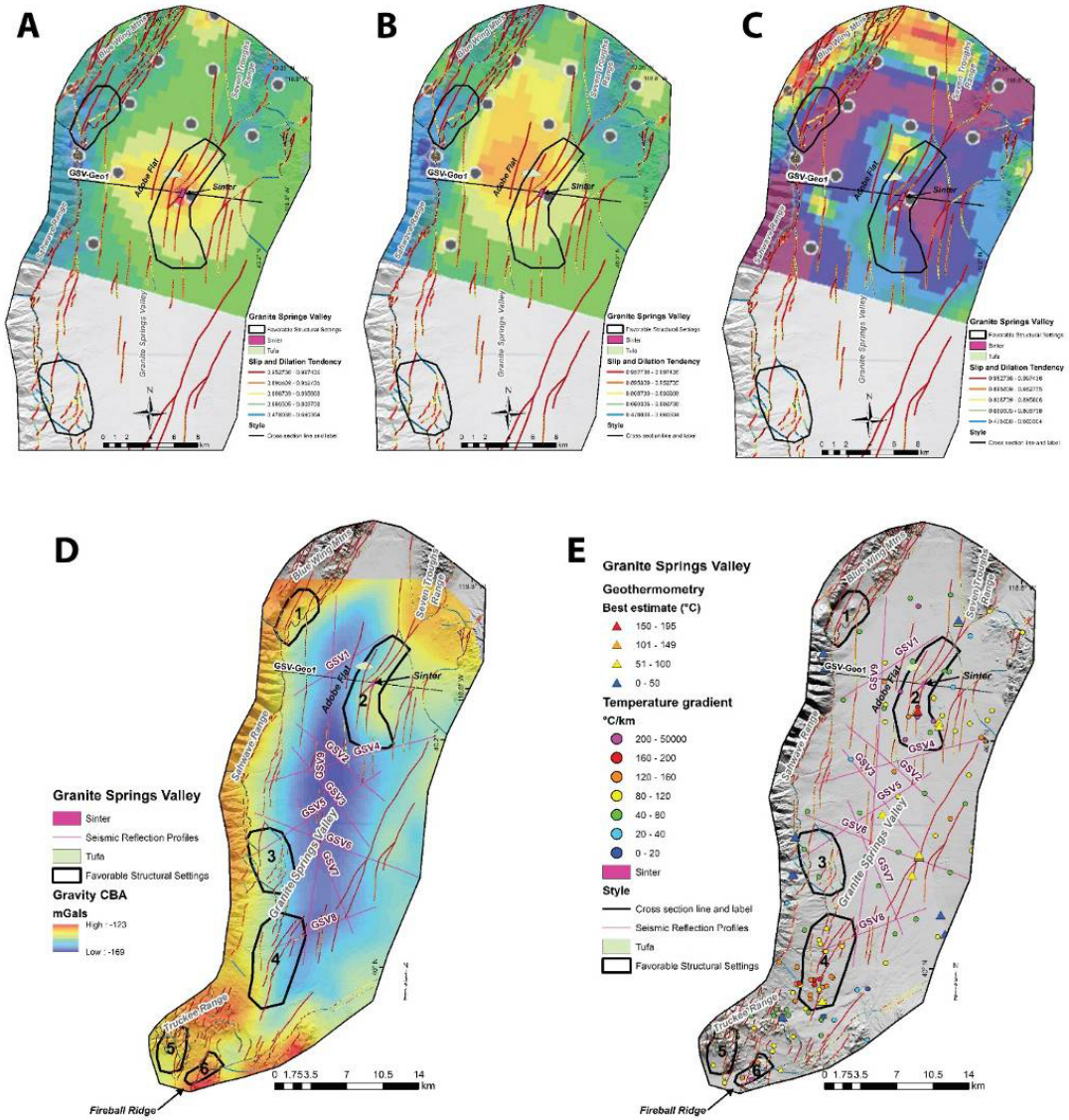




Favorable structure settings and soil gas surveying, Kumiva Valley area

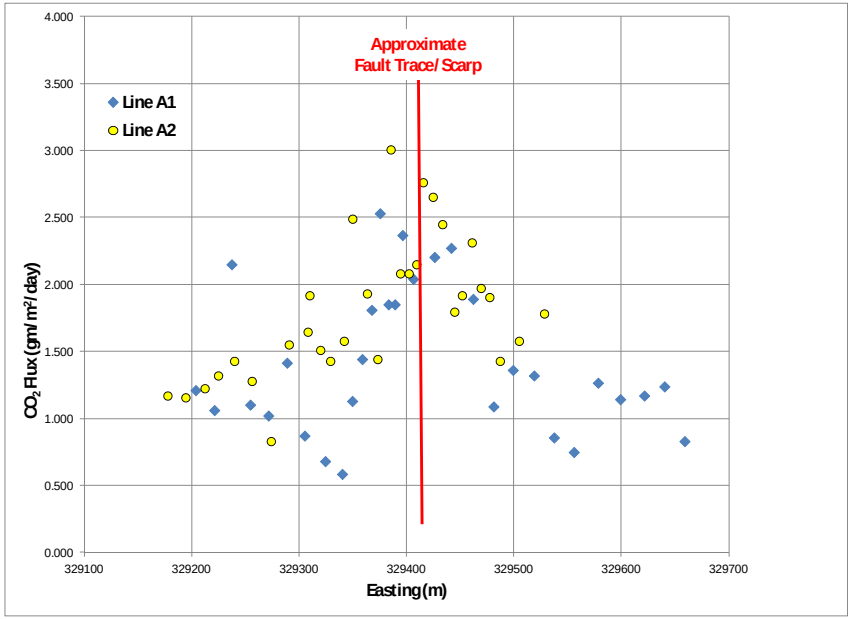
- Increased dilatency along south-central Seven Troughs Range, north Granite Springs valley, east Kumiva Valley.
- Reconnaissance soil gas profiling to cross structures.

Tech A & P

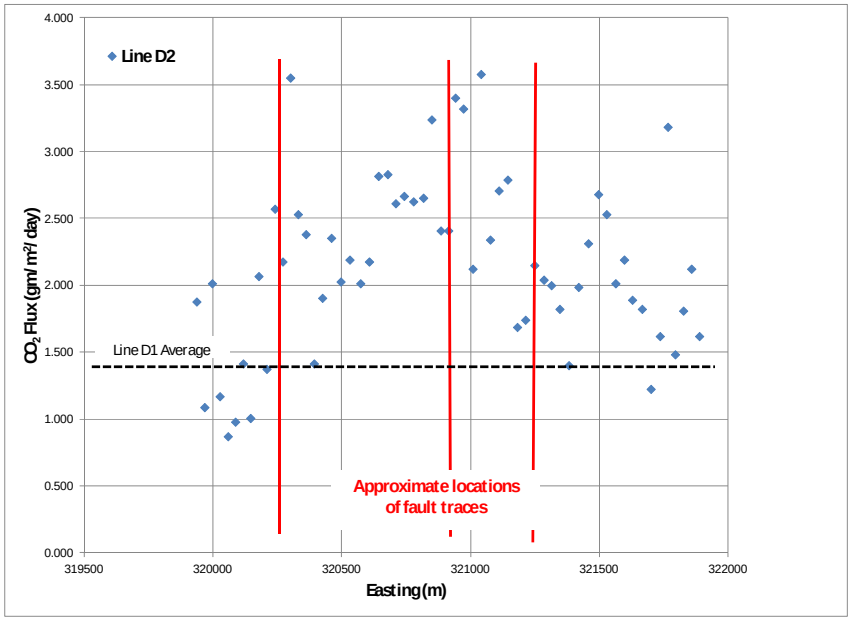


Example favorable structure settings in north Granite Springs Valley area

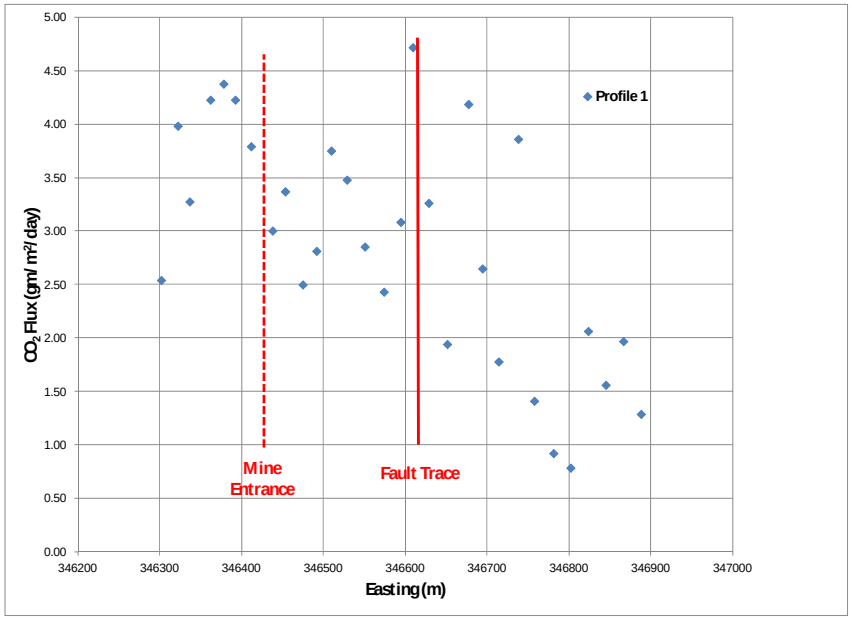
- High dilatency along shallow buried basement high, overlying moderate MT upwelling.
- Sinter/silicified sands discovered, anomalous TG values and geochem thermometry.



North Granite Springs Valley CO2 Flux



North Blue Wing Playa CO2 Flux



Seven Troughs Pass CO2 Flux

Kumiva Valley District:
Soil Gas Survey Results

Flux anomalies modest,
but permissive

Research Collaboration and Technology Transfer

- Project is joint effort between U Utah/Energy & Geoscience Inst., University of Nevada Reno, and Lawrence Berkeley National Laboratory.
- Subcontract Quantec Geoscience Inc. for MT collection.
- Several students and post-doc funded under the project.
- PI Wannamaker advises MT subcontractor on field setup (e.g., ultra-remote referencing) and response processing in areas of widespread cultural/industrial EM interference.
- Progress and results presented multiple times per year at geothermal/exploration conferences attended by industry, academia and national labs.

Future Directions

- Phase II activities ended September, 2017.
  - Phase I McGinness Hills results in comprehensive final report to the DOE/GPO, plus GRC Transaction papers. Writeup in progress for graduate thesis of student Christopher Volk.
  - Final report in progress for Phase II Kumiva Valley region field study.
  - Possible work for the future could be additional spring water sampling for major elements and 3He.

Summary

- High temperature geothermal systems in the extensional Great Basin commonly exhibit characteristic crustal resistivity structure, favorable structural dilatency, and isotope geochemical evidence of deep input.
- Characteristic MT resistivity structure was first recognized at McGinness Hills early on (2005), before significant field development.
- Partial magmatic input at McGinness Hills confirmed based on presence of 3He in well fluids.
- McGinness system lies in structural accommodation zone, the most common setting for Great Basin geothermal systems.
- Kumiva Valley region picture is more complex, although numerous MT structures and favorable geological settings are present.
- Soil gas anomalies in general are muted, but do show some presence.
- North Granite Springs valley discovered to contain mildly elevated temperatures and silicified alluvium. Other promising areas could be southern Seven Troughs area and west of Blue Wing Mtns.