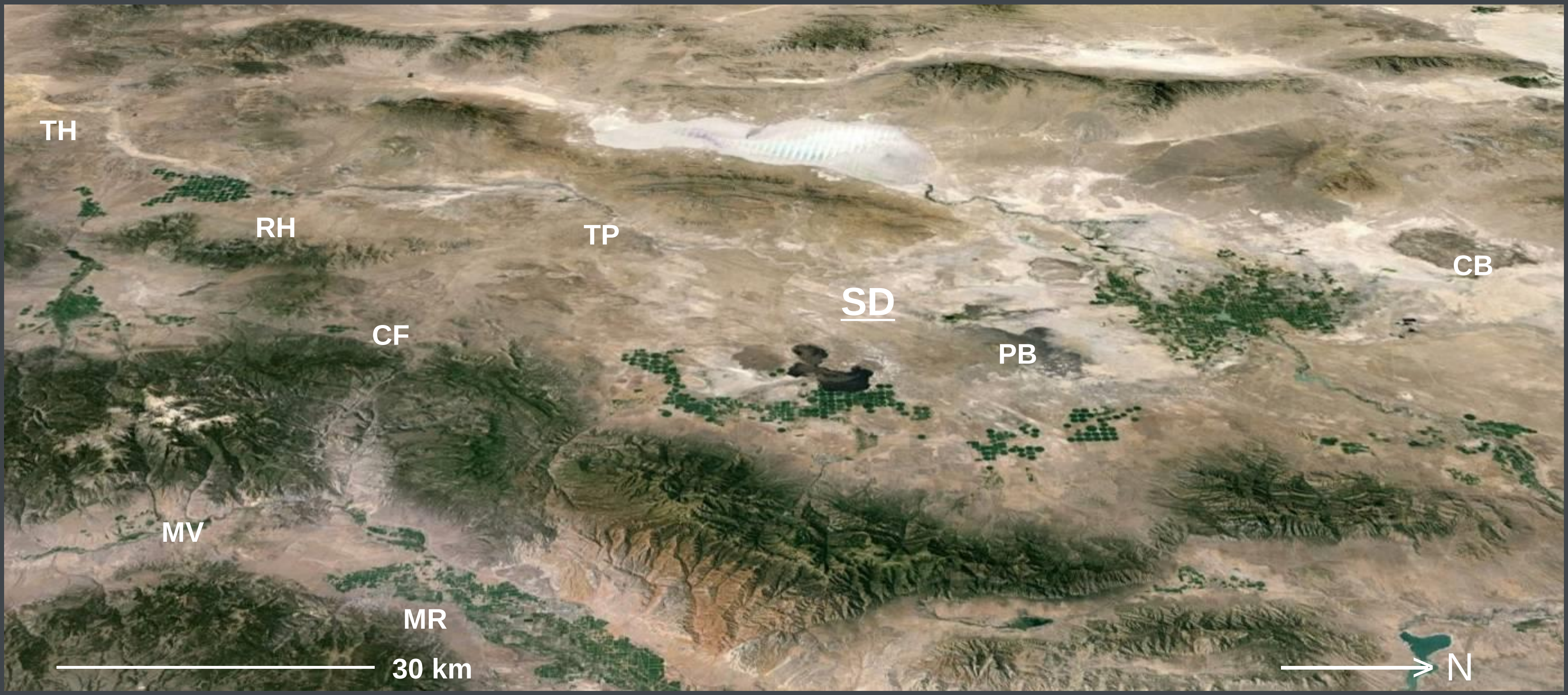
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Play Fairway Analysis (PFA): Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah

Project Officer: Mark Zeigenbein; Total Project Funding: $532,156

May 12, 2015

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Track: Exploration Validation/PFA

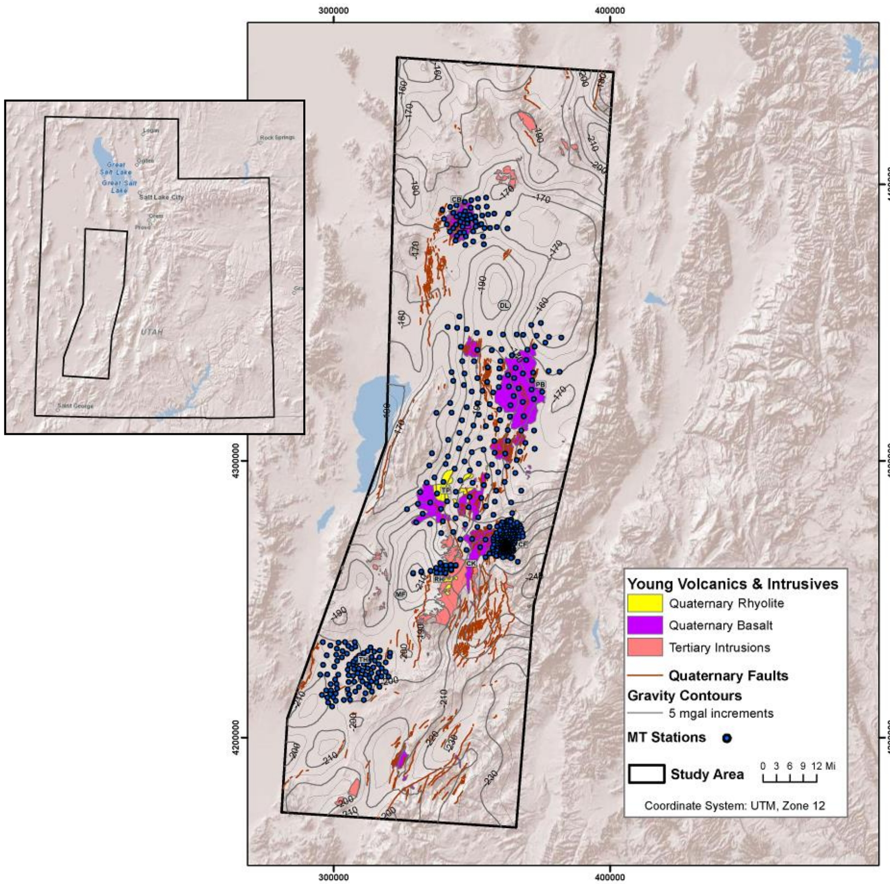
Co-I's: Kristine Pankow (U UT/GG); Joseph Moore, Gregory Nash, Stuart Simmons (U UT/EGI)

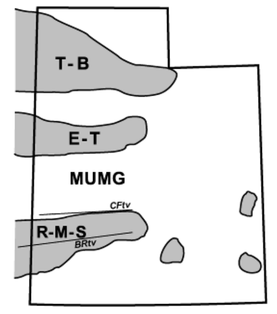
Relevance/Impact of Research

- 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*: Develop a Play Fairway Analysis (PFA) model for Eastern Great Basin, Utah; apply rigorous 3D analysis of diverse data sets; identify permeability and deep fluid sources.
- *Cost Impact*: Improved geothermal costs through new methodologies, new geothermal play model, economies of scale.
- *Innovative Aspects*: Combines unusually large MT and seismicity data sets, dilatent structural analysis, spring and well geochemistry; new 3D MT inversion method; unusually good high-T system potential.
- *Meeting GTO goals*: Intended to open an underdeveloped U.S. geothermal province; identify new plays and play types.

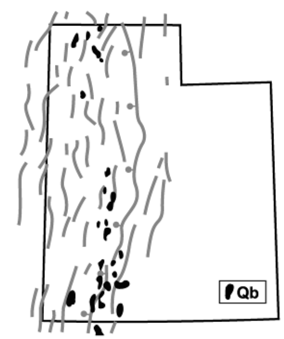
- <u>Eastern Great Basin Rationale</u>: Superposition of modern N-S striking rift axis and magmatism across E-W trending belts of plutonic basement (good reservoir rocks) and other oblique structural trends promoting dilatency.





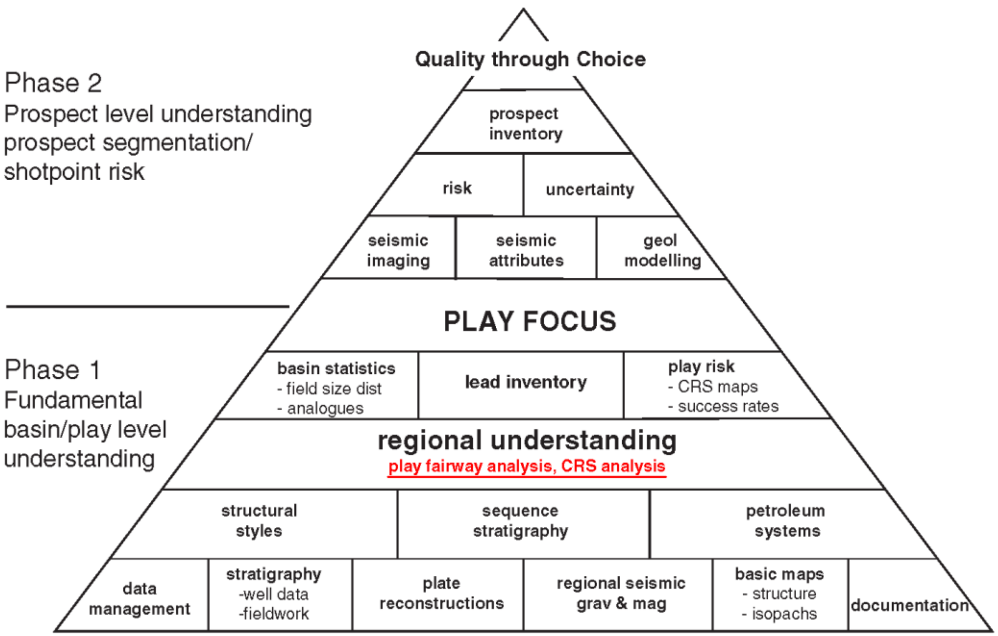
Late Eocene – Early Miocene
Silicic plutonism and ashflows

T-B=Tuscarora-Bingham plutonic belt
E-T=Eureka-Tintic plutonic belt
MUMG=Mid-Utah magmatic gap
CFtv=Cove Fort transverse zone
R-M-S=Reno-Marysvale-San Juan plutonic belt
BRtv=Blue Ribbon transverse zone

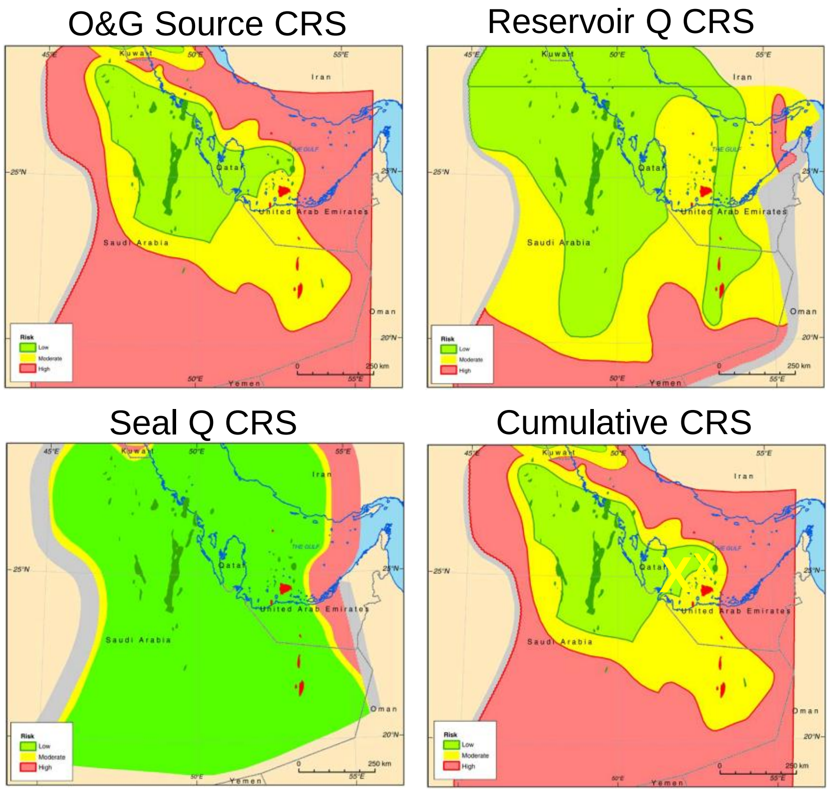


Middle Miocene – Recent
Normal block faulting, Basaltic magmatism

- PFA Approach Summary: Need to identify heat source, access to fluids, pathways to heat up and concentrate fluids, high permeability reservoir, caprock.
- Use MT to image high-T, fluidized upwellings; Test possible deep fluid zones with seismic swarms; mapping and high-res geomorphology for structural modeling; Perform major element and isotope interpretation for subsurface and fluid X-T state.



Oil & Gas Exploration Process Triangle
(A. Fraser, Geol. Soc. London, 2010)

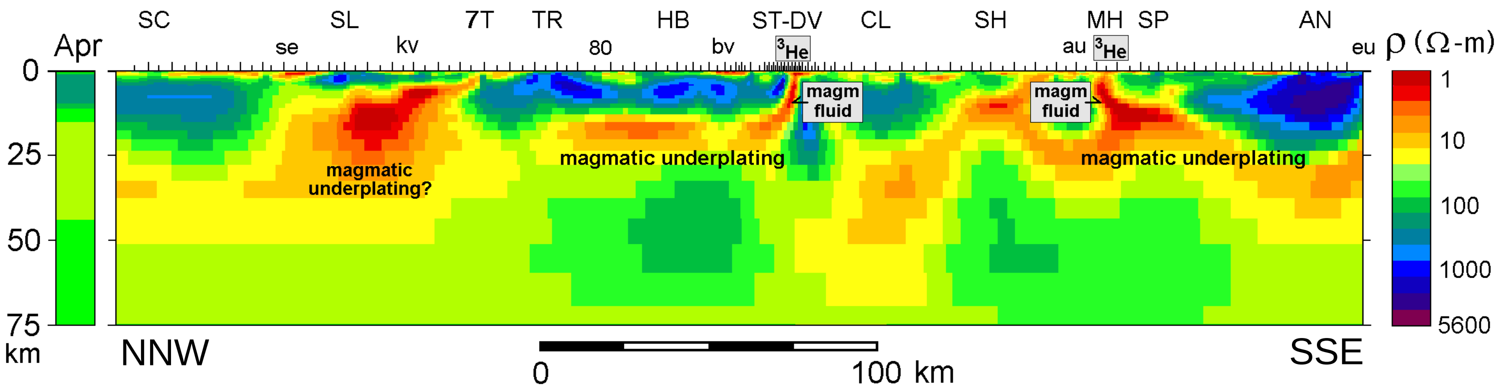


O&G CRS Analogs (Saudi Pen.)

Approach

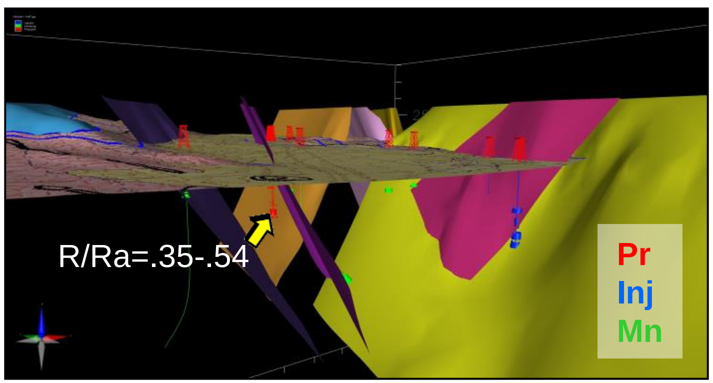
Great Basin Magmatism & McGinness Hills System

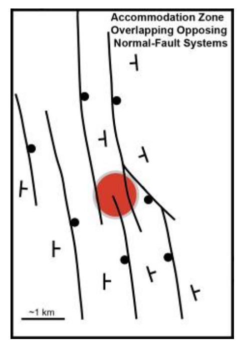
Motivation for Method Integration in Eastern Great Basin



- Structural setting as accommodation zone
- Deep magmatic connection from elevated R/Ra
- CO_2 flux anomaly along ~NW fault zone

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

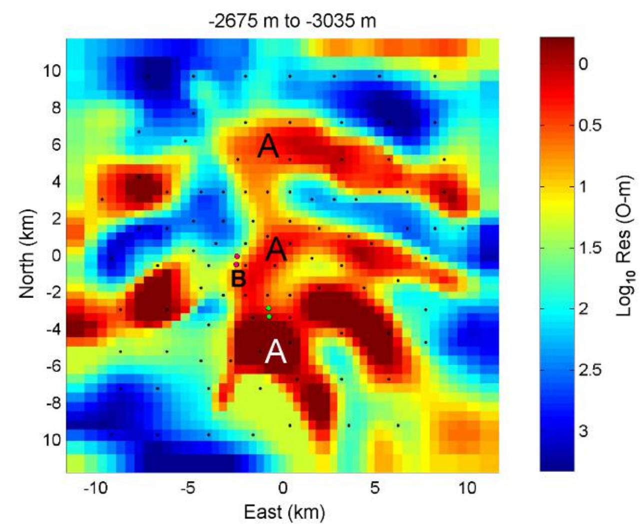




after J. Faulds

⇧ 3D structural perspective view from mapping and wells; ^{3}He R/Ra in production wells

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



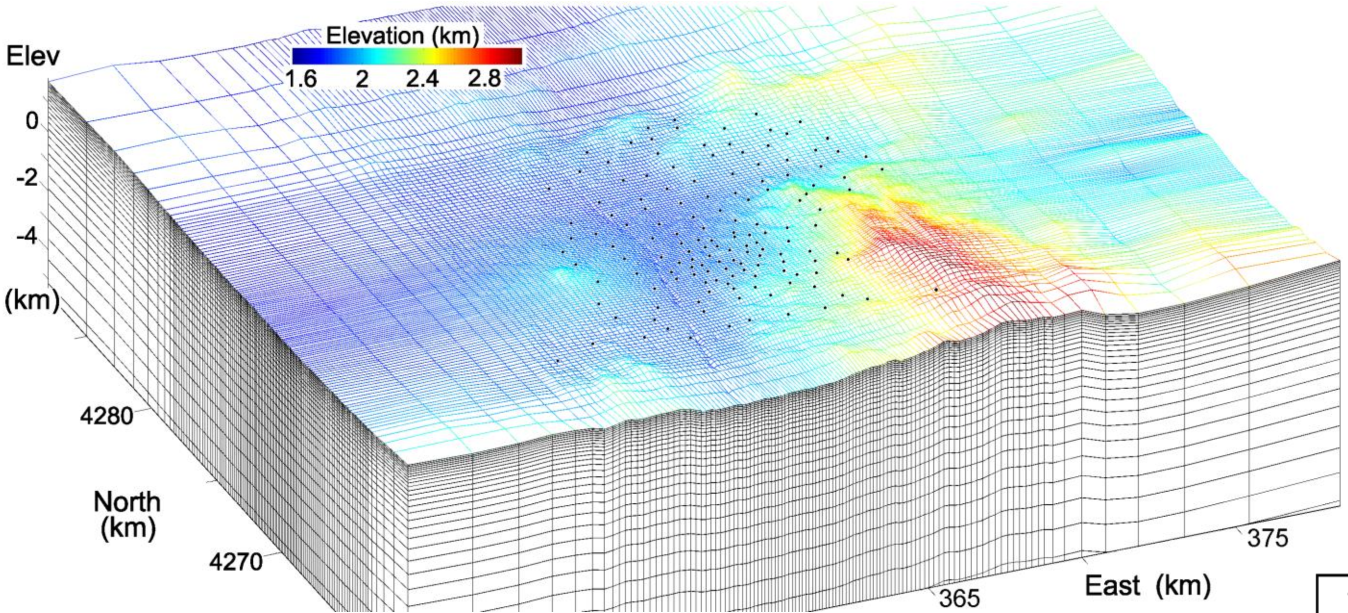
3D MT Resistivity Plan View

B is production, A is deep regional

U.S. DOE contract DE-EE0005514

Approach

Advances in 3D MT Imaging



< Finite Element Mesh
Cove Fort, Utah

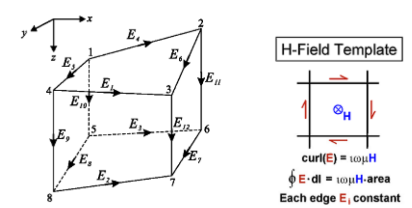
Objective:	$W_\lambda(m) = \{(d - F[m])^T C_d^{-1}(d - F[m])\} + \lambda\{(m - m_o)^T C_m^{-1}(m - m_o)\}$
NL Step:	$m_{k+1} - m_k = \{J_k^T C_d^{-1} J_k + \lambda C_m^{-1}\}^{-1}\{J_k^T C_d^{-1}(d_k - F[m_k]) - \lambda C_m^{-1}(m_k - m_o)\}$

Stabilized Iterative Earth Resistivity Voxel 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

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

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

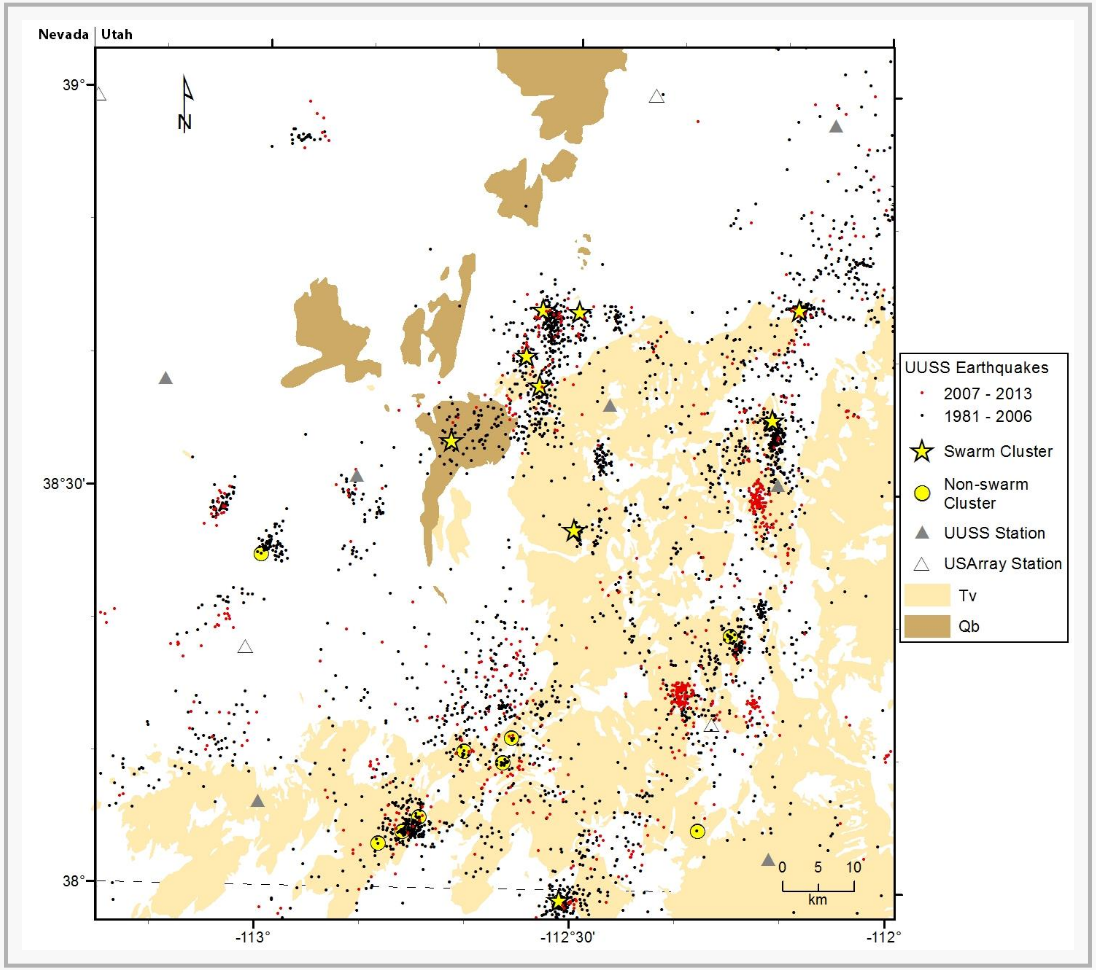
$$E = \sum_{i=1}^{n_e} x_i N_i \qquad H = \frac{-\nabla \times E}{i\omega}$$



EM Field (Maxwell) Equations
And Deformed Finite Element

3D MT Inversion Using Deformable Edge Finite Element Algorithm
(Kordy, Wannamaker, et al., 2015, revised)

Advances in Seismicity Analysis

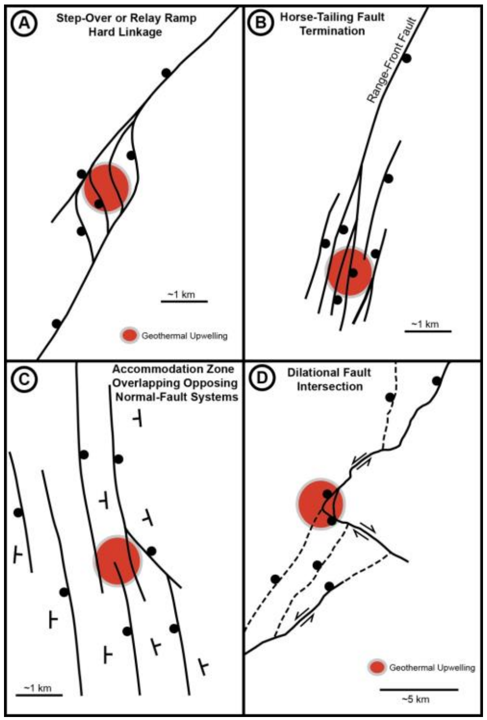


Southwestern Utah Seismicity from University of Utah Seismograph Stations and Earthscope USArray Stations

- Eastern Great Basin is seismically active
- Standard Omori-type seismicity can reveal fault zone trends
- Seismic swarms may reveal fluid flow or ductile deformation
- Swarm clusters from Arabasz et al (2007) were subcontracted using propriety software with unclear selection parameters – need to be re-examined
- New waveform correlation techniques may improve event detectability by 1-2 orders of magnitude
- PFA Phase I task is test new clustering and detection techniques to verify existing swarms and increase events within identified swarms

•Capabilities in Structure, Geophysics, GIS Database

A GIS database has been developed that includes:

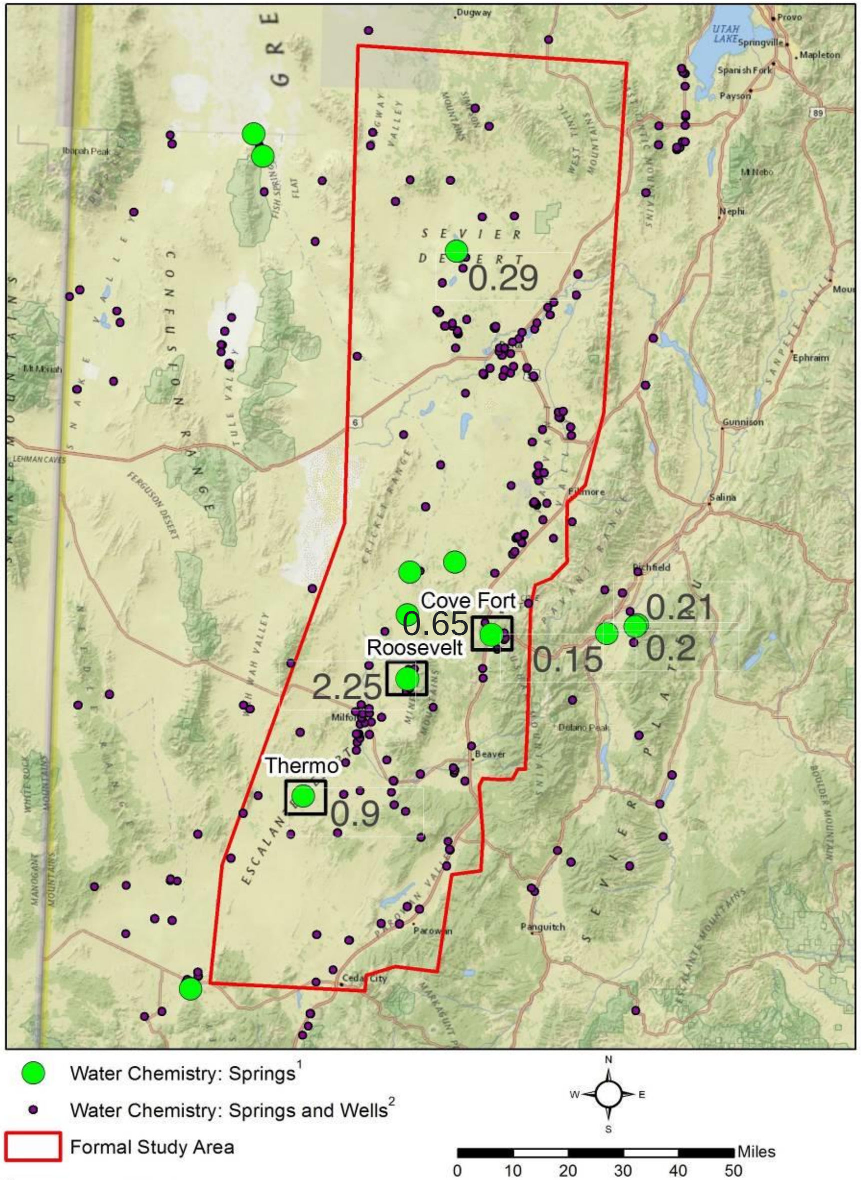


Example dilatent structures (after Faulds et al, 2013) that can serve as points of departure for this study.

- Quaternary faults
- Total fault offset
- Regional strain
- Regional dilation
- Regional shear
- Regional Bouguer gravity
- Regional total magnetic
- MT Resistivity Volumes
- Temperature gradients
- Geologic maps covering the area
- Structural areas of interest (AOIs)
- Digital elevation model (DEM)
- Shaded relief
- Nighttime surface temperature anomalies from ASTER
- Water chemistry
- Heat flow
- Lake Bonneville shoreline

Structural analysis is intended to identify zones of long-lived dilatency (inherently 3D) and to correlate them with deep-seated MT and seismicity anomalies and with fluid geochemistry

Geochemical Analysis and Geological Modeling



[1] Cole, D. R., 1983. Chemical and isotopic investigation of warm springs associated with normal faults in Utah, Journal of Volcanology and Geothermal Research, 16, pp 65-98.

[2] Blackett, R.E., and Wakefield, S.I., 2002, Geothermal resources of Utah, a digital atlas of Utah's geothermal resources: Utah Geological Survey, OFR-397, CD-ROM.

Map showing locations of springs and thermal areas within the study area, based on the UGS (Blackett and Wakefield, 2002) and Cole (1983). Numbers represent R/Ra $^3He/^4He$ data (Kennedy and van Soest, 2007).

- Chemical and isotopic analyses illuminate compositions of the rocks hosting the geo-thermal reservoirs, fluid sources, ages, and pathways and deep reservoir temperatures.
- Geochemical models of deep fluid flow pathways and sources will be correlated with geophysical and geological structures, to identify potential buried plays within fairway.
- Conceptual models of geothermal systems will be developed integrating geophysics, geology and geochemistry.

Accomplishments, Results and Progress

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Proposed Milestones at Outset of Project:

Milestone Summary Table							
Recipient Name:		University of Utah/EGI (Philip E Wannamaker, P.I.)					
Project Title:		Structurally Controlled Geothermal Systems in the Eastern Great Basin Extensional Regime, Utah					
Task Number	**Task Title or Subtask Title (If Applicable)**	**Milestone Type (Milestone or Go/No-Go Decision Point)**	**Milestone Number* (Go/No-Go Decision Point Number)**	**Milestone Description (Go/No-Go Decision Criteria)**	**Milestone Verification Process (What, How, Who, Where)**	**Anticipated Date (Months from Start of the Project)**	**Anticipated Quarter (Quarters from Start of the Project)**
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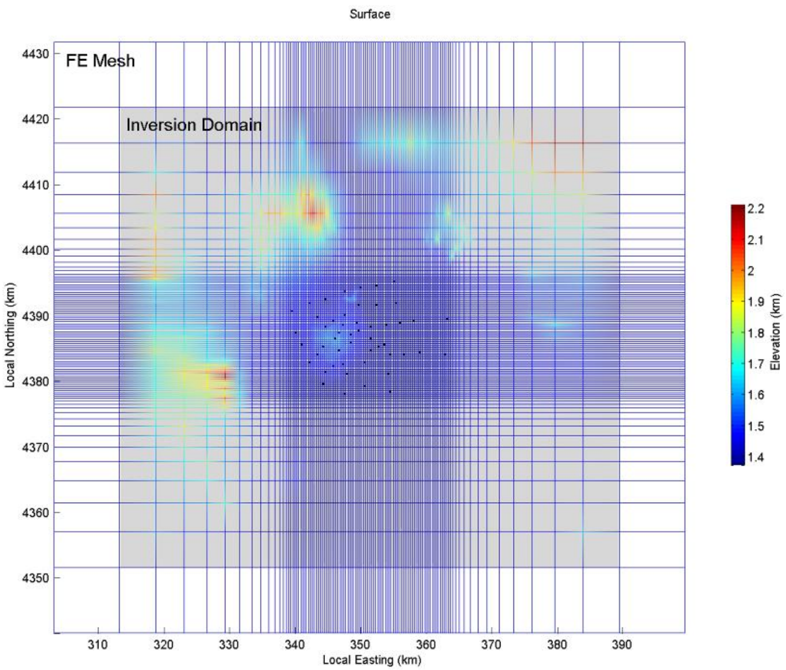
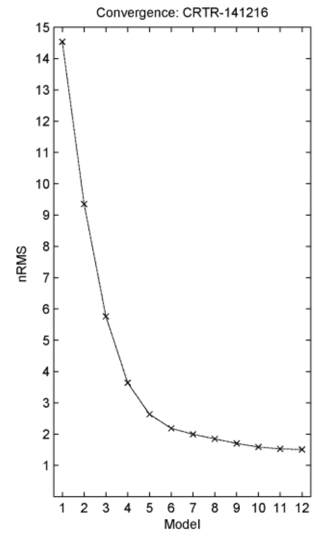
T3.2	Dilatency Analysis	Milestone	M3.2	Permeability Potential	Permeability Potential Map to Group, feedbk	9	3
T4.1	Fluid Chemistry Compilation	Milestone	M4.1	Readiness for Chem Modeling	Present. of distribution to group, feedback	3	1
T4.2	Chem Modeling Geological Model	Milestone	M4.2	Geochem Model Geological Model	Thermal Conditions Map to Group, Feedbk	9	3
T5.1	Integration	Milestone	M5.1	Fairway Map Production	Exchange of Individual Fairway Maps, Exchange of Composites, Feedback	12	4

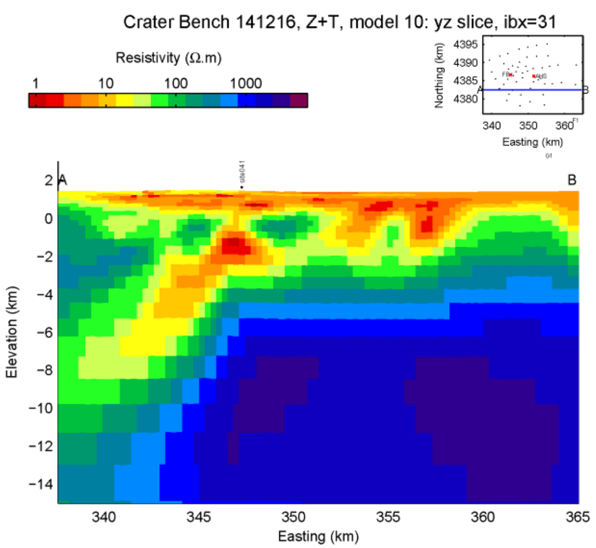
- Project is on time and on budget in each of the stated subtasks above.
- 3D MT inversion shows pertinent conductive geothermal upwellings.
- New prospective structures from geomorphology and gravity.
- New fluid subsurface T estimates and fluid history modeling.

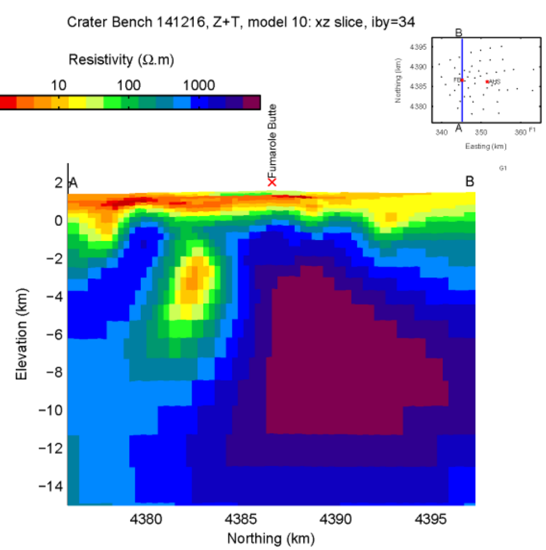
Results

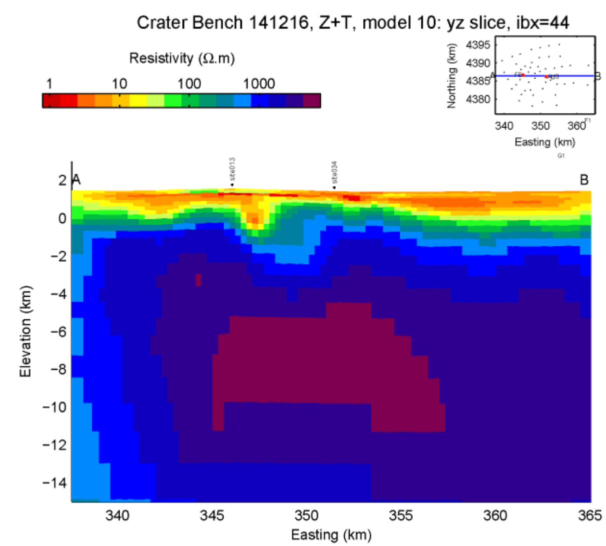




- 50 MT stations, 25 periods (0.02 - 80 s)
- Sub Rx: min cell = 300 m w
- FE mesh: 91 (n) x 111 (e) x 43 (z) cells (10 air)
- Inversion domain: 88 x 108 x 30 = 285,120 parameters
- Error floors: 3.5% max{ |Zij| ; |Zxy-Zyx|/2 }, 0.03 tipper
- 33 ohm-m starting model, nRMS = 1.5 after 12 iters
- 4.8 hours/iter on 24-core w/s with 0.5 TB RAM







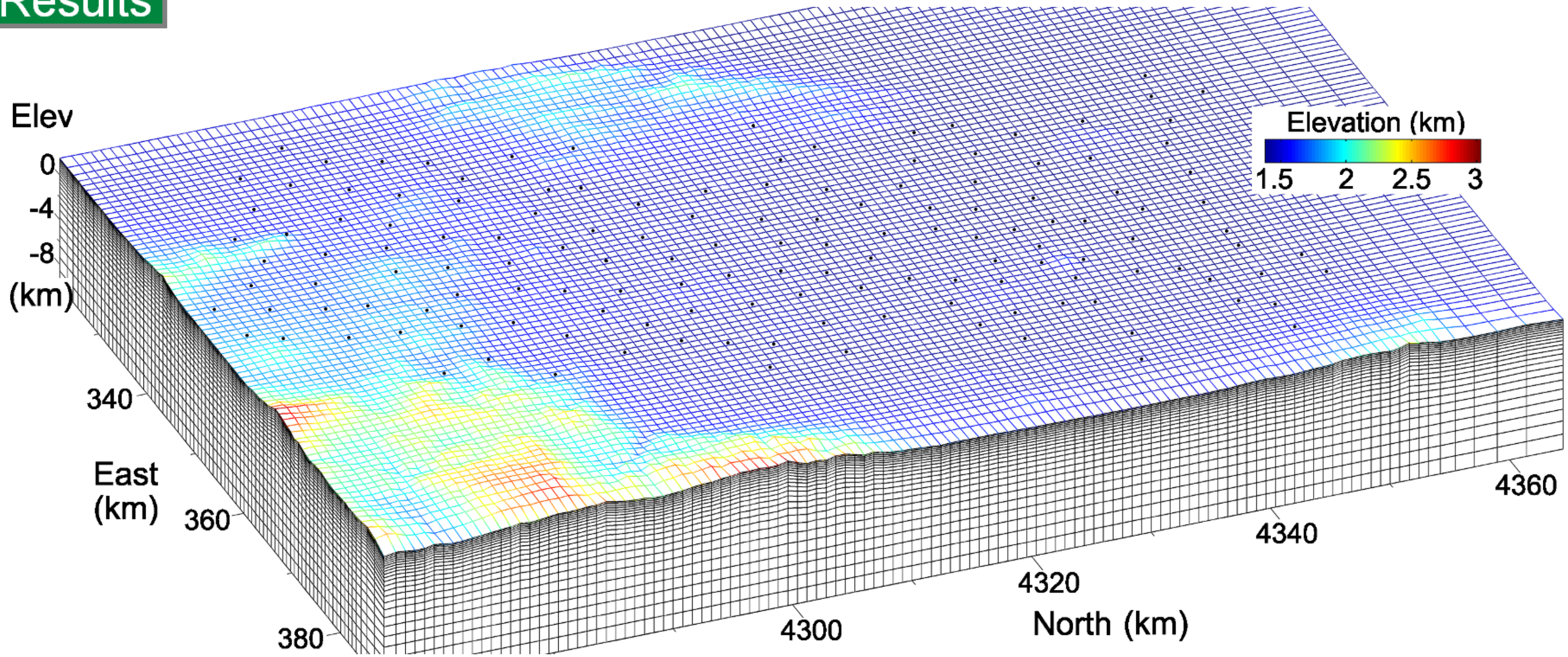
Crater Bench 3D MT Inversion: No deep source root under Abraham HS

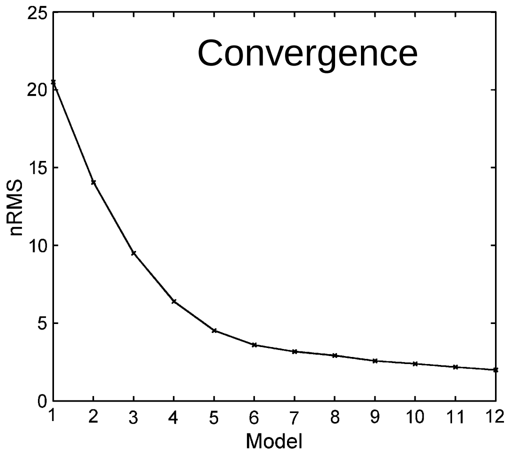
A possible deep source projects from south toward the crater

Extrusive may have erupted along contact with very resistive body (pluton?)

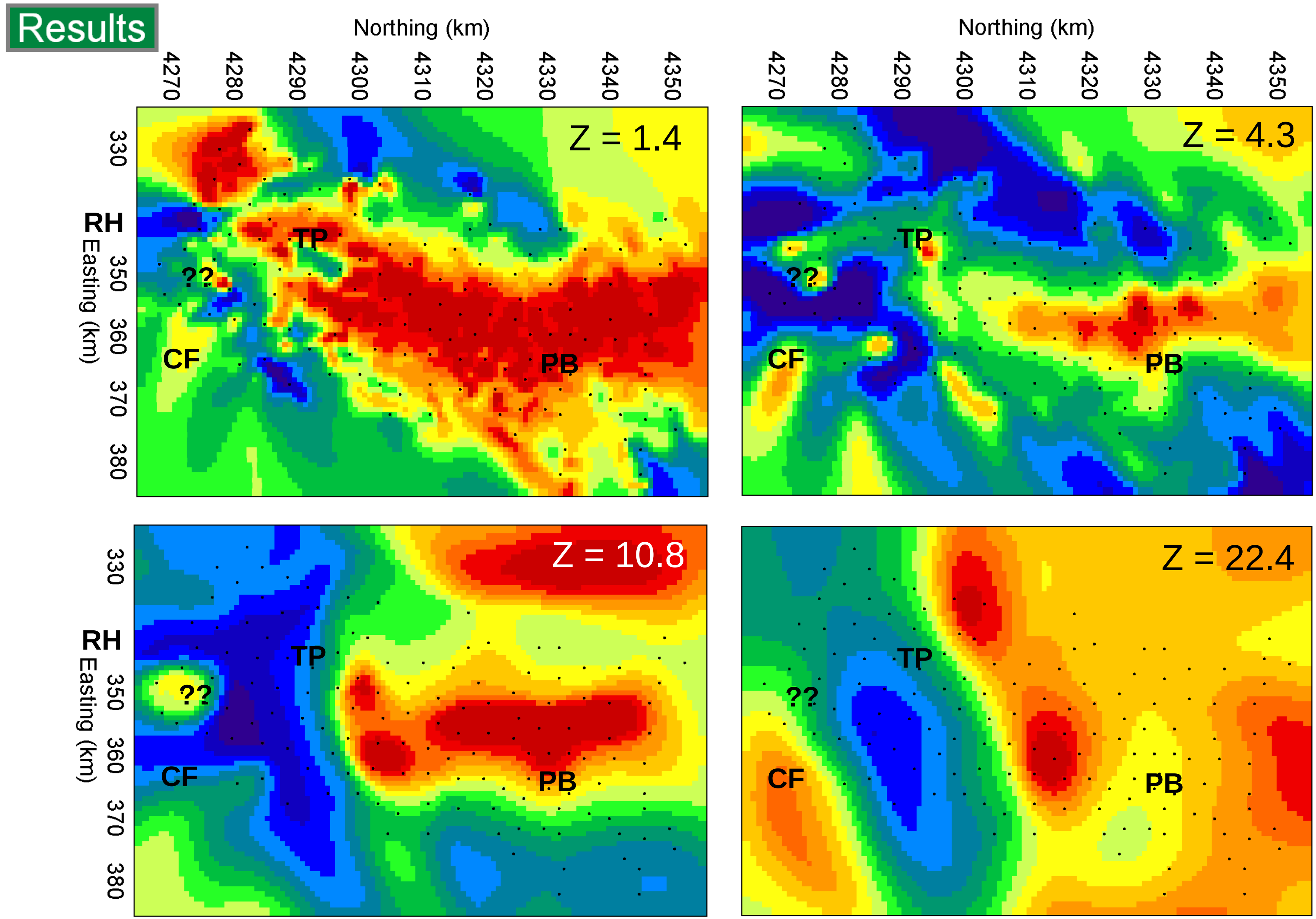
3D MT Inversion Edge Finite Element Mesh: Broader Sevier Basin

Results





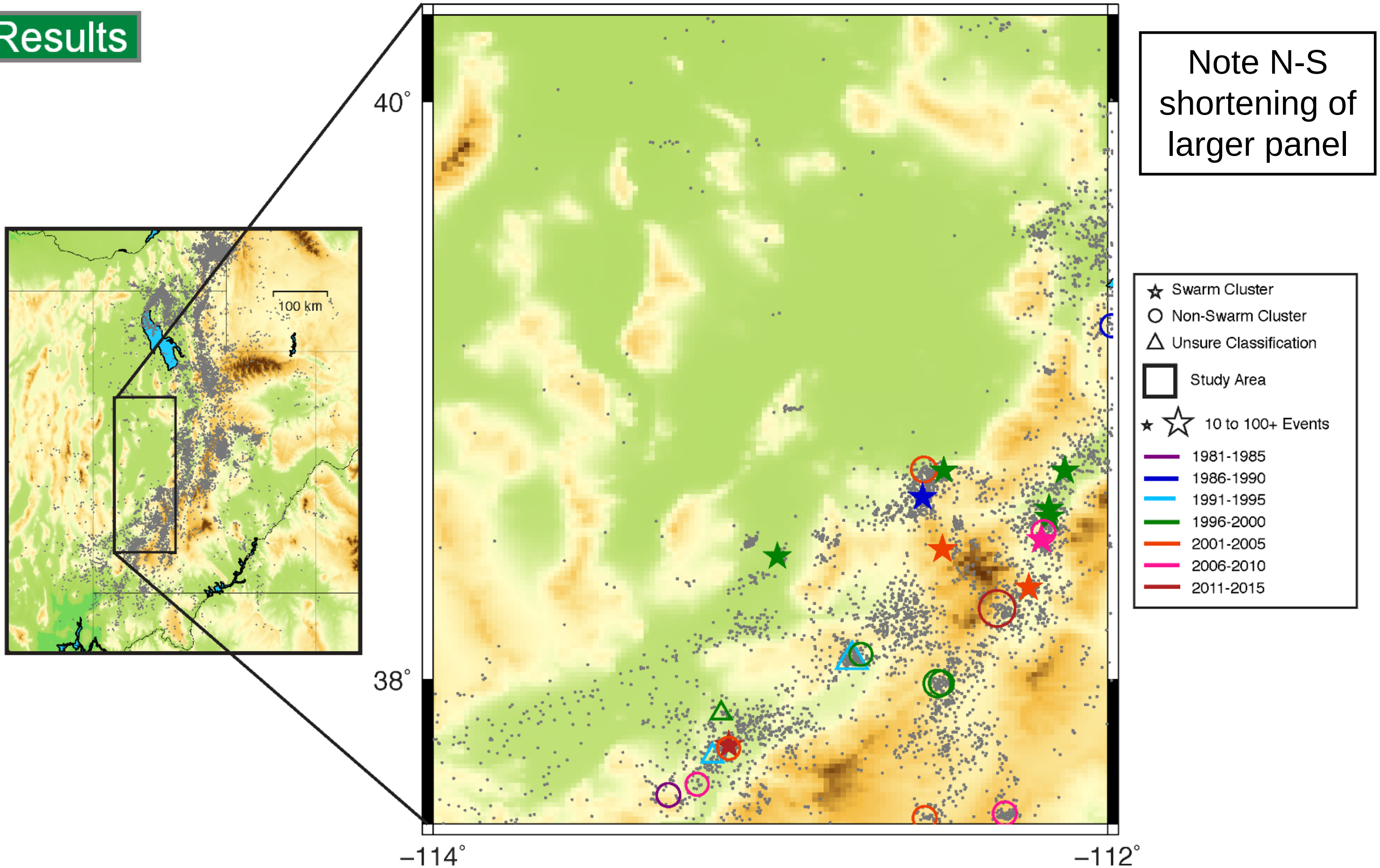
- 143 MT stations, 24 periods (0.08 to 212 s)
- Sub Rx: min cell = 0.8 km w, 0.1 km z
- FE mesh: 135 (n) x 99 (e) x 47 (z) cells (12 air)
- Inversion domain: 132 x 96 x 32 = 405,504 parameters
- Error floors: 3.5% max{ |Zij| ; |Zxy-Zyx|/2 }, 0.03 tipper
- 20 ohm-m starting model, nRMS = 2.3 after 10 iters
- 12 hours/iter on 24-core w/s with 0.5 TB RAM



Sevier Basin 3D MT Inversion Model: Plan Views to Depth

Radical change across the Cove Fort transverse zone from Sevier Basin onto Marysvale plutonic belt
Localized conductive upwellings near Twin Peaks (TP), Cove Fort (CF), and Cinder Knolls (??) trend

Results



Note N-S shortening of larger panel

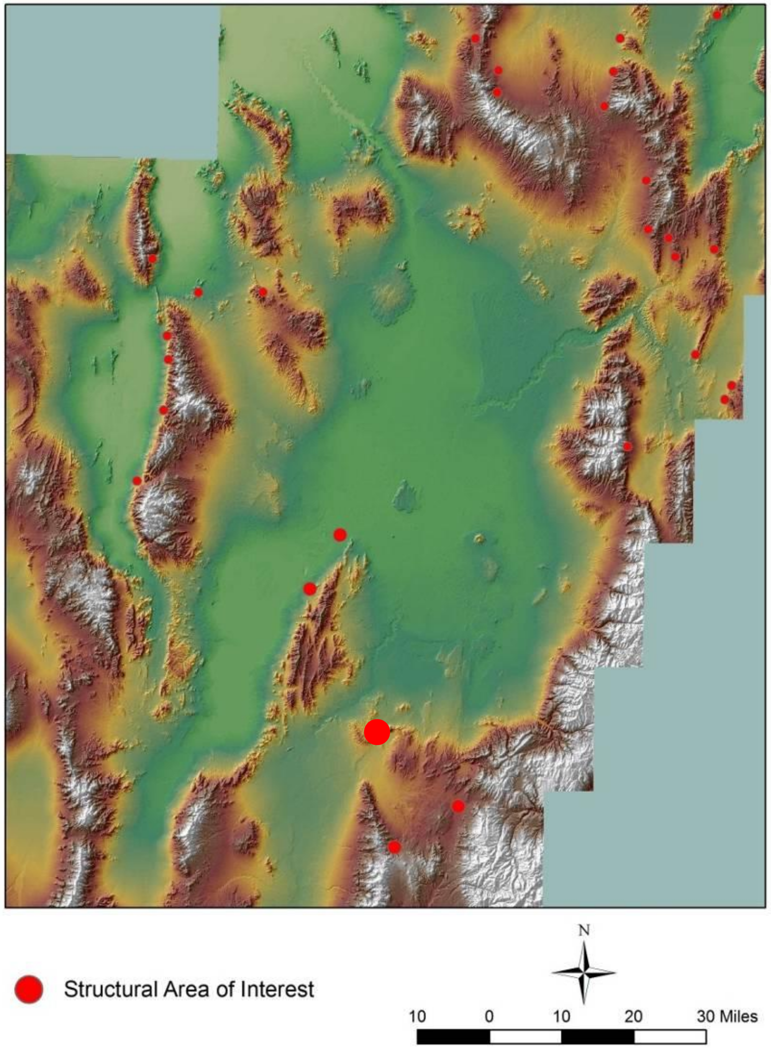
Preliminary New Seismicity Clustering Analysis of SW Utah Events

Most swarm and non-swarm events from Arabasz et al (2007) confirmed

No diffusive swarm movement has been detected to date

<u>Work in progress</u>: also to compare with MT and geological structure

Structural Areas of Interest

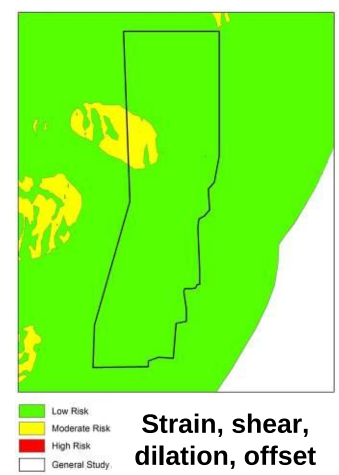


Thirty structural areas of interest (AOIs) have been identified thus far. They represent geometries known to produce critical stress. Great Basin geothermal systems in the possess these geometries. The current AOIs represents normal fault step-overs, normal fault tips, accommodation zones, and a suspected relay ramp. Analysis is based on geomorphologic and gravity data interpretation. Intent is to continue south through the project area.

AOIs have been recognized throughout the eastern Great Basin, in addition to the formal play fairway project area.

Elements of Extension

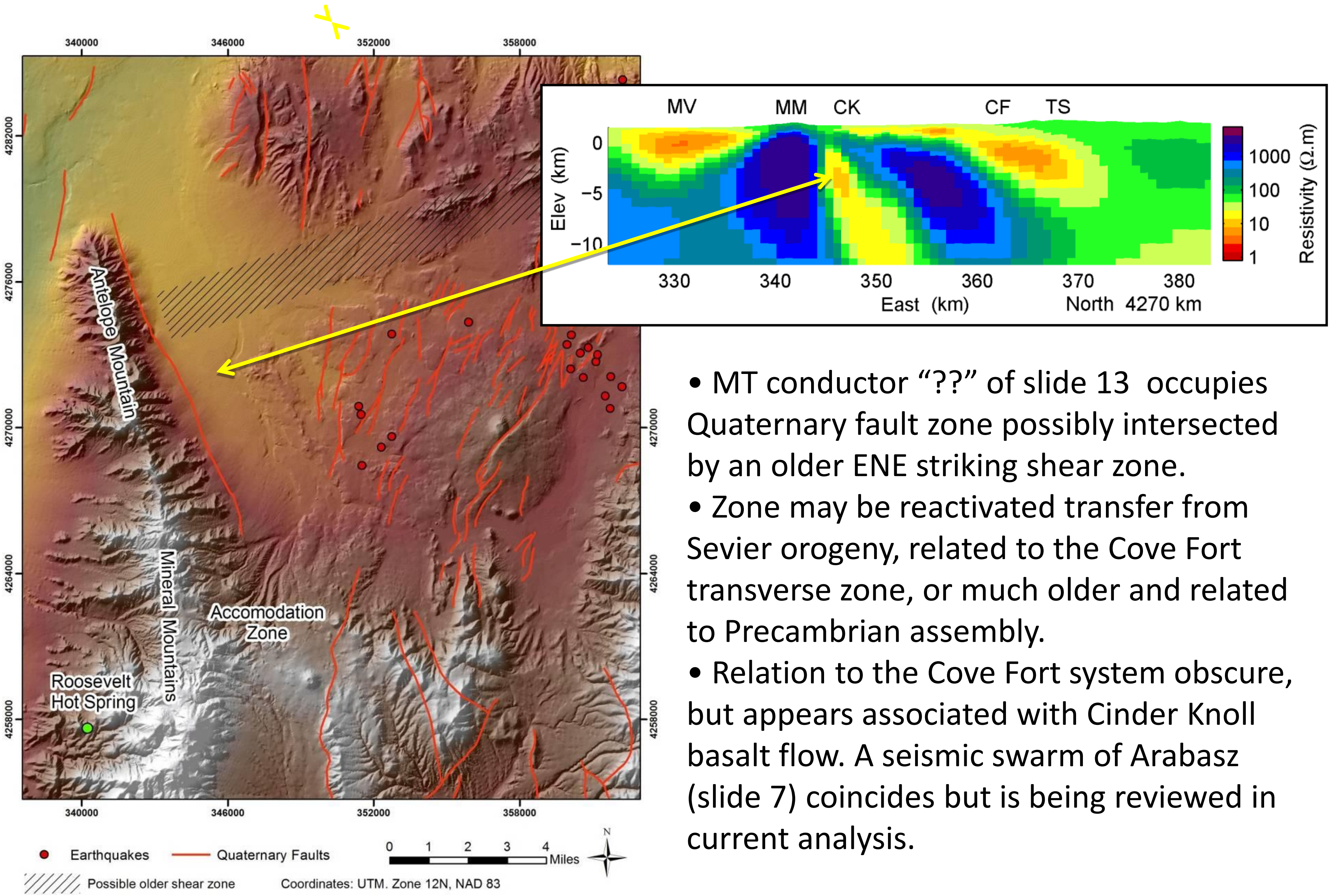
Most geothermal systems in the Great Basin have one of: high strain, dilation, shear, and/or total fault offset. Data representing these elements of extension were classified and fused into this layer of evidence, to be used as part of the structural composite risk segment. No high risk areas lacking all indicators are found within the study area.



Strain, shear, dilation, offset

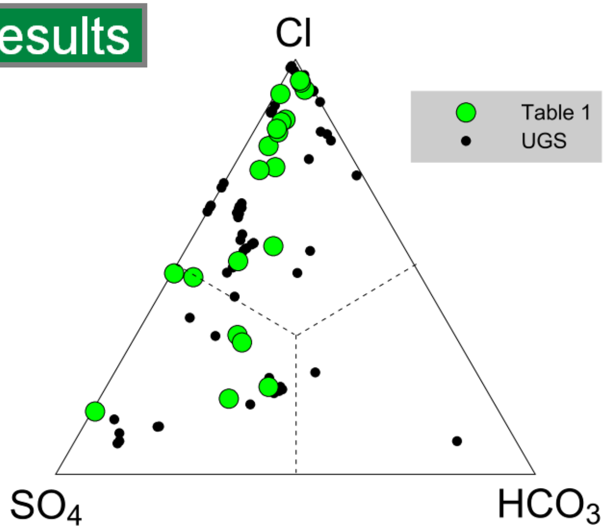
Results

Structurally Related MT Conductor

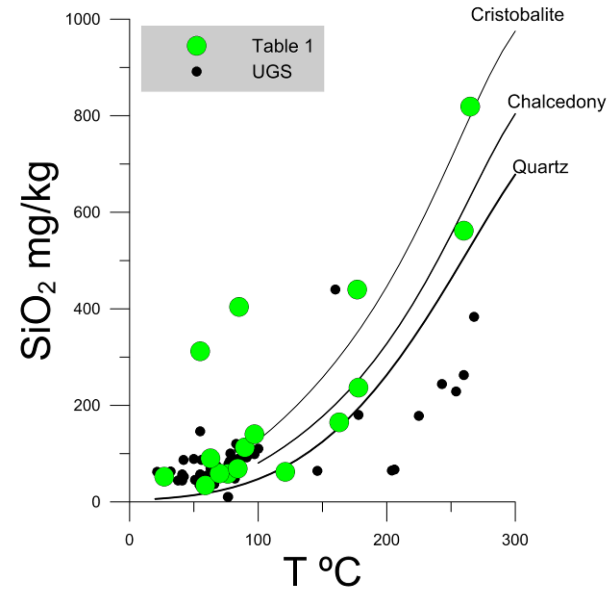


- MT conductor "??" of slide 13 occupies Quaternary fault zone possibly intersected by an older ENE striking shear zone.
- Zone may be reactivated transfer from Sevier orogeny, related to the Cove Fort transverse zone, or much older and related to Precambrian assembly.
- Relation to the Cove Fort system obscure, but appears associated with Cinder Knoll basalt flow. A seismic swarm of Arabasz (slide 7) coincides but is being reviewed in current analysis.

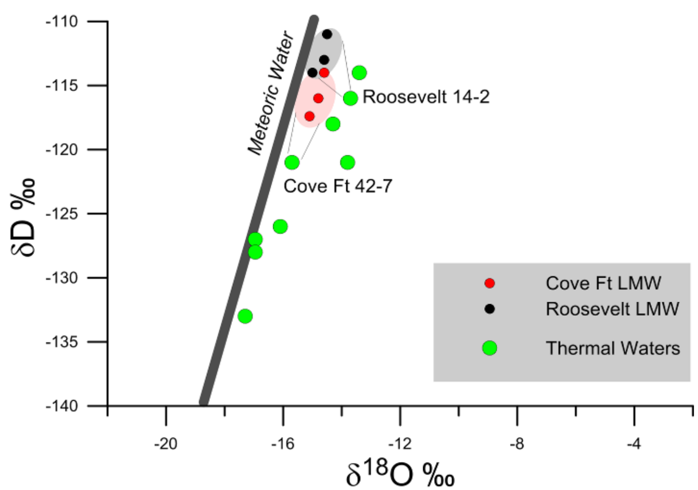
Results



Major anions in thermal waters



Aqueous silica vs temperature



Stable isotopes in thermal waters near Roosevelt and Cove Fort HS

Geochemical Analysis and Geological Modeling

- Roosevelt and Cove Fort have similar Cl and SO_4 despite differing reservoir rocks
- O and H isotopes show high-T exchange but also that reservoir waters may be Pleist glacial
- Elevated ^3He R/Ra implies magmatic input
- Na/K temps tend to exceed measured suggesting Si geothermometer may be more reliable
- Volcanic rocks unexpectedly prominent at depth at Cove Fort in addition to carbonates

Future Directions

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- Our strategy is intended to provide focus for followup exploration and development in this area of possible high geothermal potential. Table presents project year plan going forward.
- Future activities for FY2015:
  - Complete cataloging of possible geothermally-relevant, low-resistivity upwellings.
  - ID of new faulting esp. to south in area, dilatency analysis for permeability potential.
  - Spring chemistry modeling, interpretation of ultimate fluid sources and reservoir rocks.
  - Derivation of characteristic geothermal model(s) for Eastern Great Basin.
  - Presentation of possible play areas for followup assessment.
  - Identification of data needs and next steps in the region, including possible slimhole drilling.

Summary

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- Eastern Great Basin should have high geothermal potential given active rifting, magmatism, good reservoir rocks, dilatent structures.
- Integration of MT resistivity, structural analysis and fluid geochemistry constitutes methodology for prioritizing exploration and play ranking.
- Low-resistivity upwellings resolved using new MT inversion capability may equate to shallower high temperatures and fluids; will complete inversions with Cove Fort and expanded Sevier Basin.
- New seismic clustering and waveform correlation techniques have been tested, confirm swarm and non-swarm events from earlier catalogue and promise to improve detectability and reliability significantly.
- Numerous favorable structural settings identified from mapping and geo-morphology.
- State-of-the-art geochemical modeling allows equilibrium or reaction-based subsurface fluid temperature estimates with rigor beyond standard geothermometry.
- PFA will move southward through Thermo Hot Springs area with progress.