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Geothermal Fault Zone and Fluid Imaging through Joint Airborne ZTEM and Ground MT Data Inversion

Contract DE-EE0007697

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Project Officer: Michael Weathers; Total Project Funding: $632,925

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Track 2: SubTER

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Relevance/Impact of Research

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- 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*: Reduced undersampling in geothermally pertinent electrical resistivity through efficient integration and joint 3D inversion of ground and airborne natural field EM data.
- *Cost Impact*: Improved geothermal costs through new methodologies, and better efficiencies in existing methodologies.
- *Innovative Aspects*: Combines airborne plane wave EM method prominent in mining exploration with ground MT to increase sampling and remove ambiguity. Analysis includes new joint 3D inversion platform incorporating topography using deformable finite elements.
- *Meeting GTO goals*: Project is aimed at reducing upstream risk in geothermal resource development by providing improved subsurface imaging.

Scientific/Technical Approach

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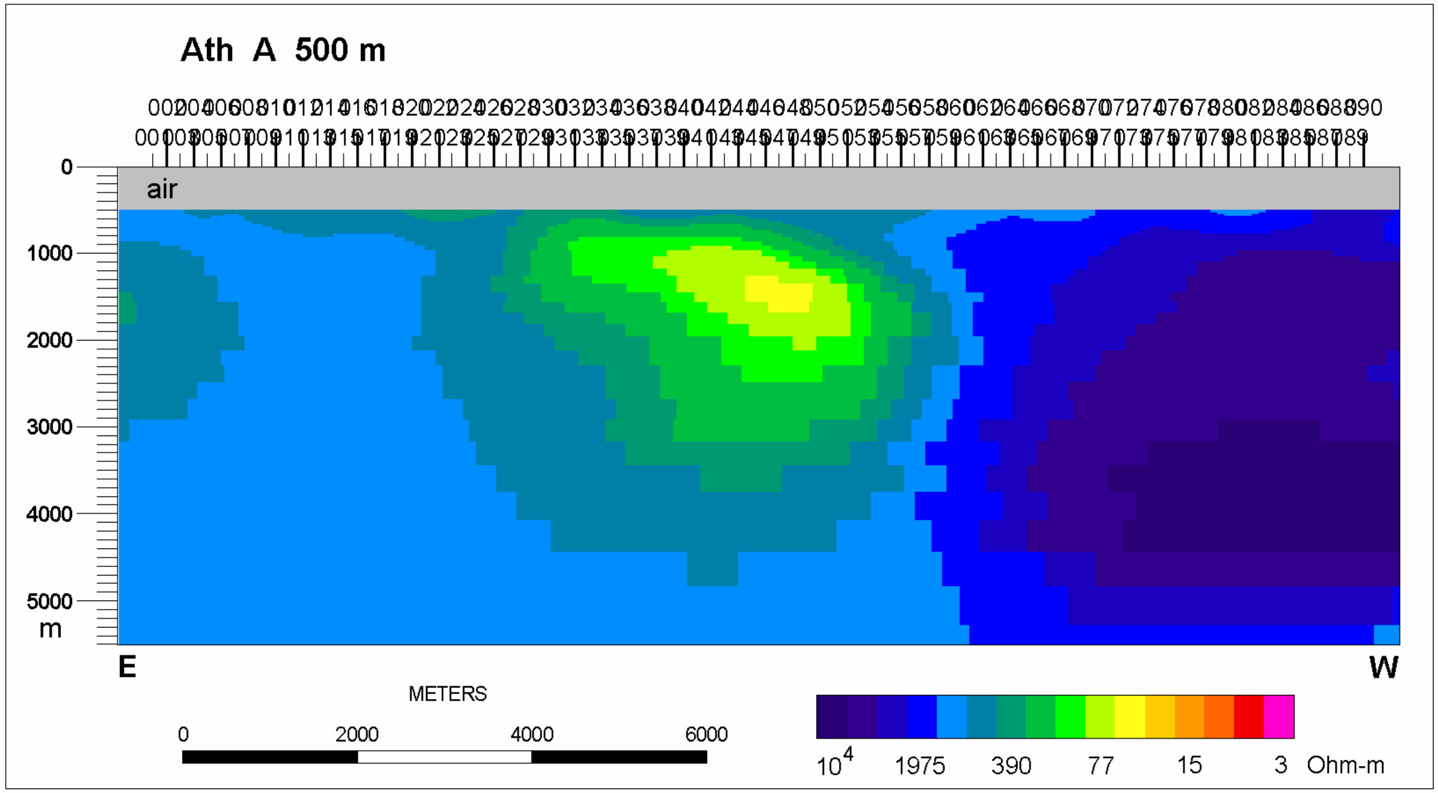
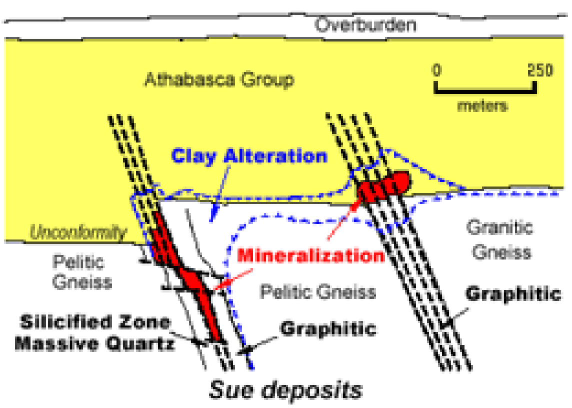
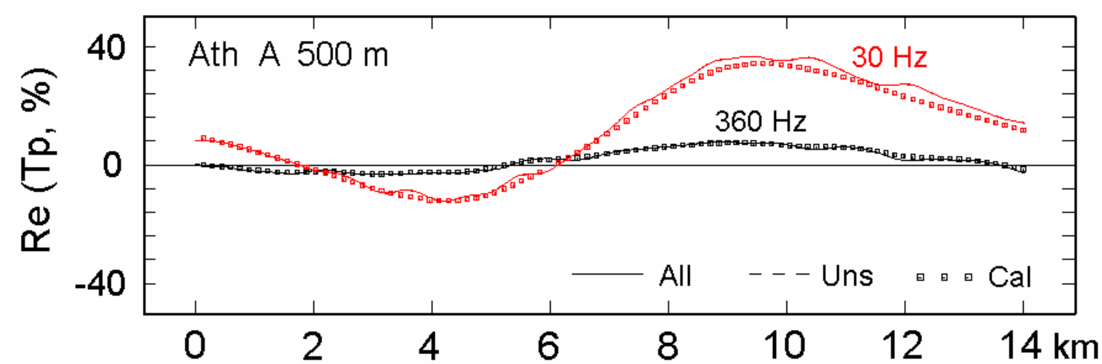
- Task 1- Project Mgmt: Project requires incorporation of survey and imaging methodologies not previously implemented. We leverage airborne EM technology (ZTEM) developed for the mining industry with ground MT commonly used in geothermal. Newly developed 3D EM inversion for joint data is the most capable in existence. First year almost exclusively devoted to field surveying, second year to analysis.
- Task 2- ZTEM Surveying: Test method at Roosevelt Hot Springs (RHS) high-T geothermal system with ~700 line km spanning system and central Mineral Mountains (MMts).
- Task 3- ZTEM Response Estimation: Improve ZTEM low frequency data and thus depth of exploration by applying jackknife outlier removal.
- Task 4- MT Surveying: Well sampled collection over RHS and central MMts adequate to stand on its own for sampling, but can allow subsampling with ZTEM to test survey efficiencies.
- Task 5- Joint Inversion Model: Apply newly developed 3D finite element platform for separate and joint ZTEM/MT data inversion to test relative resolving capability of data combinations.
- Task 6- System Update: Select promising structures may be tested with passive ^{3}He soil gas detectors. Geologic model of the RHS and MMts will be updated as appropriate from results.

Geotech Inc. ‘ZTEM’





Athabasca Basin Unconformity
Uranium Deposits

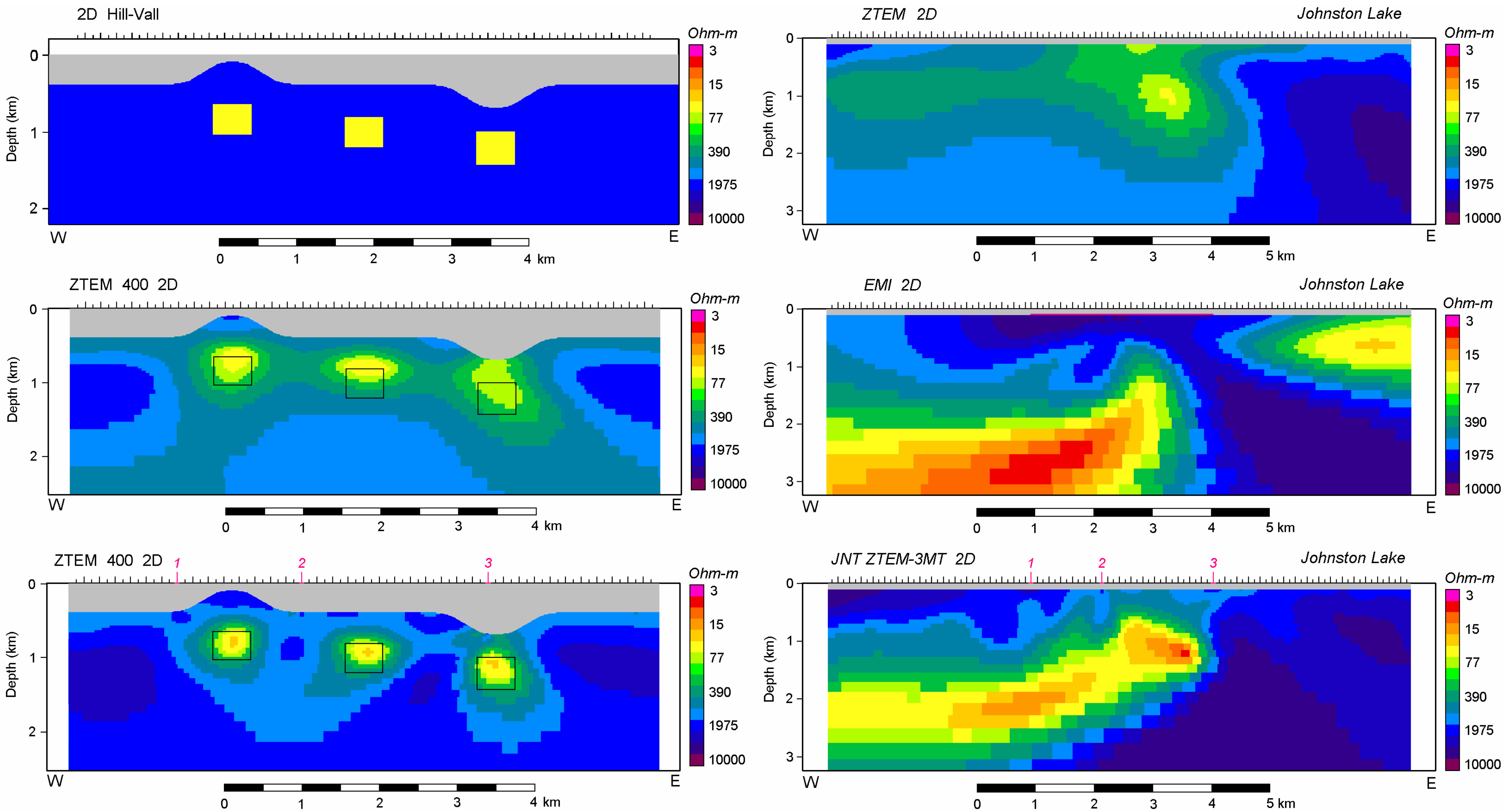


Airborne MT Tipper Measurements for Deep Mineral Exploration

- Inversion possible with suitable host constraints
- Excellent recon for detailed ground follow-up

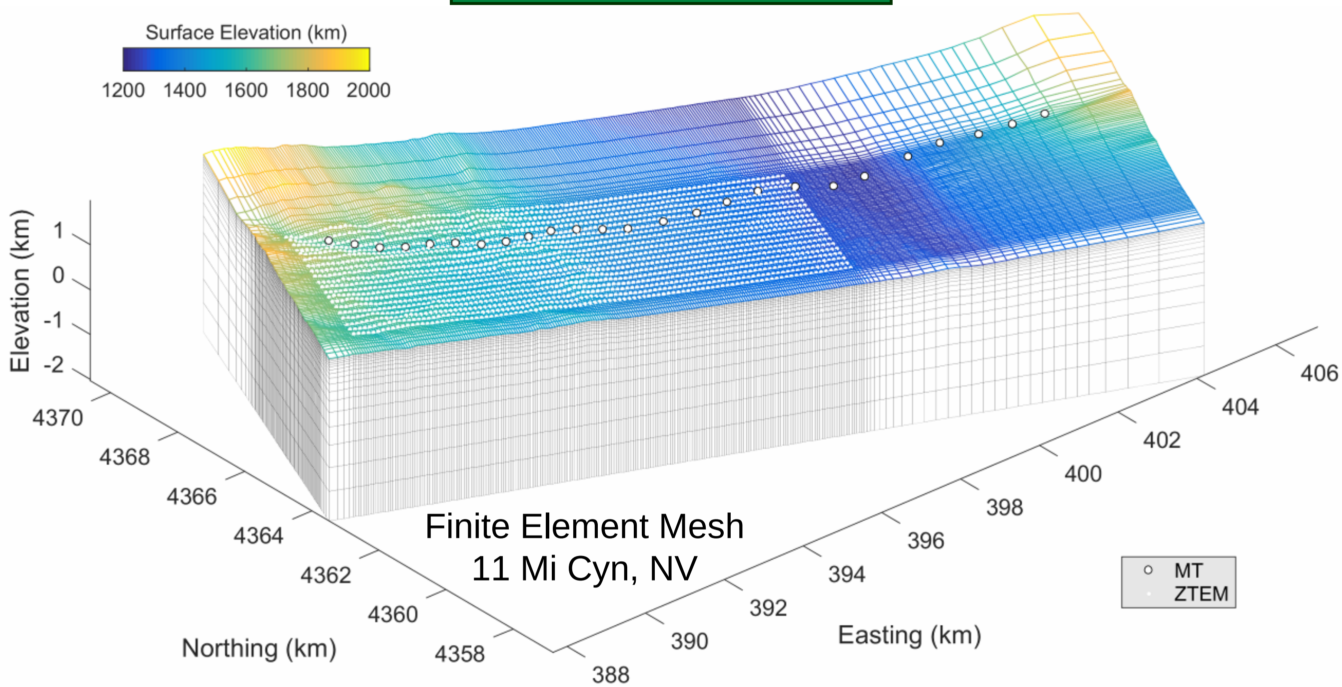
Methods/Approach

Methods/Approach



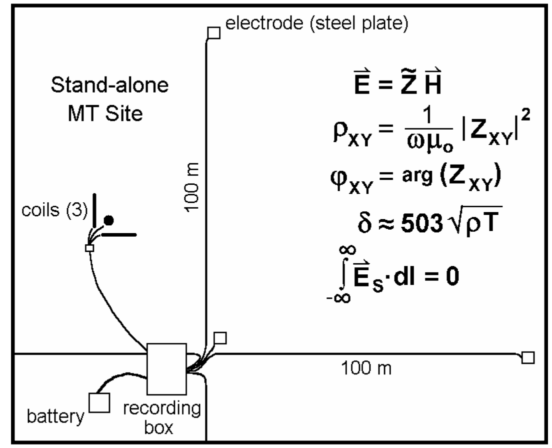
<u>Motivation:</u> 2D Joint Airborne ZTEM/MT Inversion Test: Synthetic Prism Model with Topo (left), plus Johnston Lake Uranium Prospect , Canada (right)

Methods/Approach



Finite Element Mesh
11 Mi Cyn, NV

MT Schematic

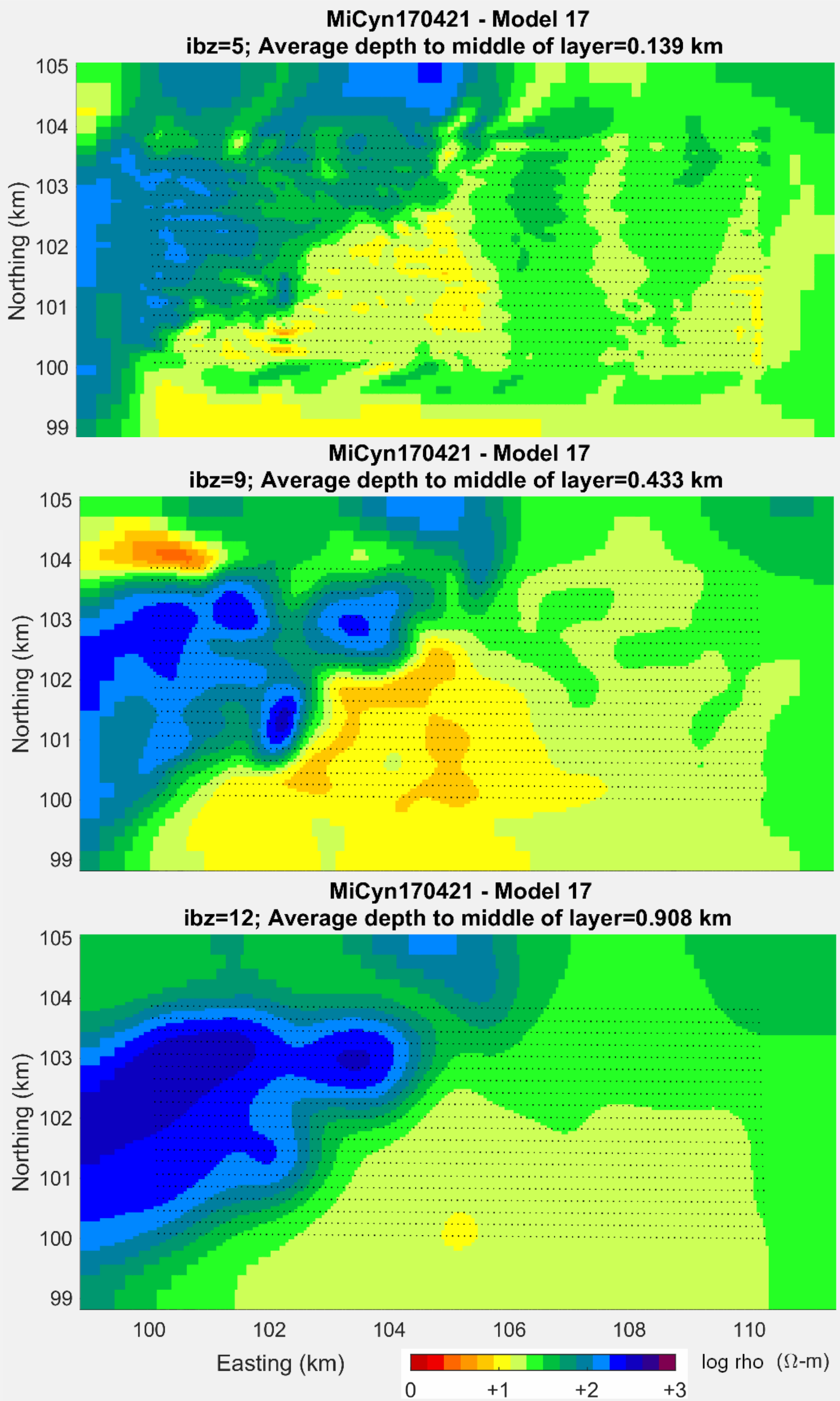


Objective:	$W_\lambda(m) = \{(d - F[m])^T C_d^{-1}(d - F[m])\} + \lambda\{(m - m_o)^T C_m^{-1}(m - m_o)\}$
NL Step:	$m_{k+1} - m_k = \{J_k^T C_d^{-1} J_k + \lambda C_m^{-1}\}^{-1}\{J_k^T C_d^{-1}(d_k - F[m_k]) - \lambda C_m^{-1}(m_k - m_o)\}$

Stabilized Iterative Earth Resistivity Voxel Estimation
Non-Linear Model Step Recast to Data-Space Formulation
Direct Matrix Solutions Used Throughout (Pardiso, Plasma)
ZTEM Data, Response and Jacobians Append to MT Arrays
Parallelized on Large RAM, Single-Box Workstations

ZTEM Airborne EM Loop

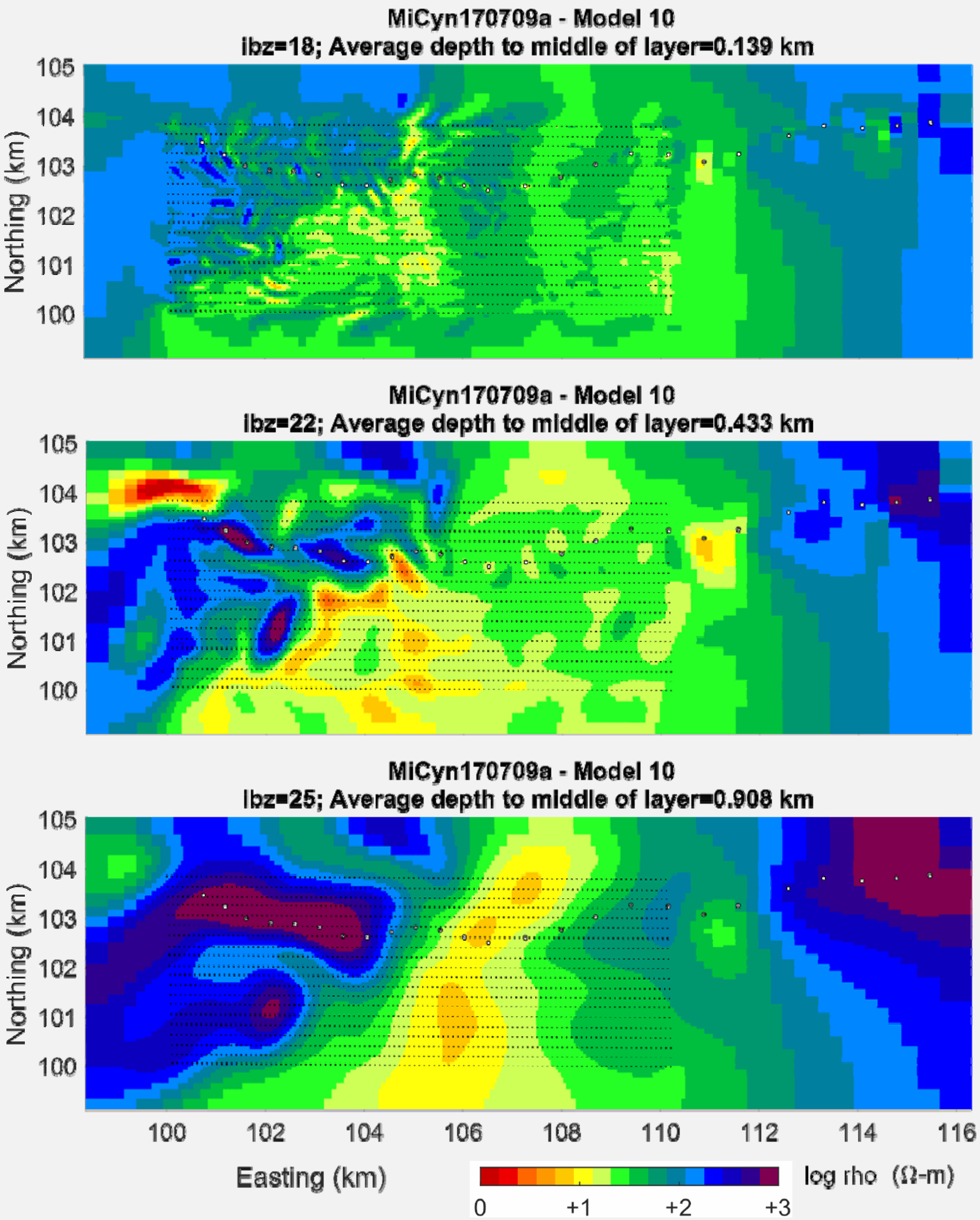
3D MT Inversion Using Deformable Edge Finite Element Algorithm
(Kordy, Wannamaker, et al., 2016, GJI) (DE-EE0002750)
Starting Point for Joint ZTEM/MT Data Inversion



Methods/Approach

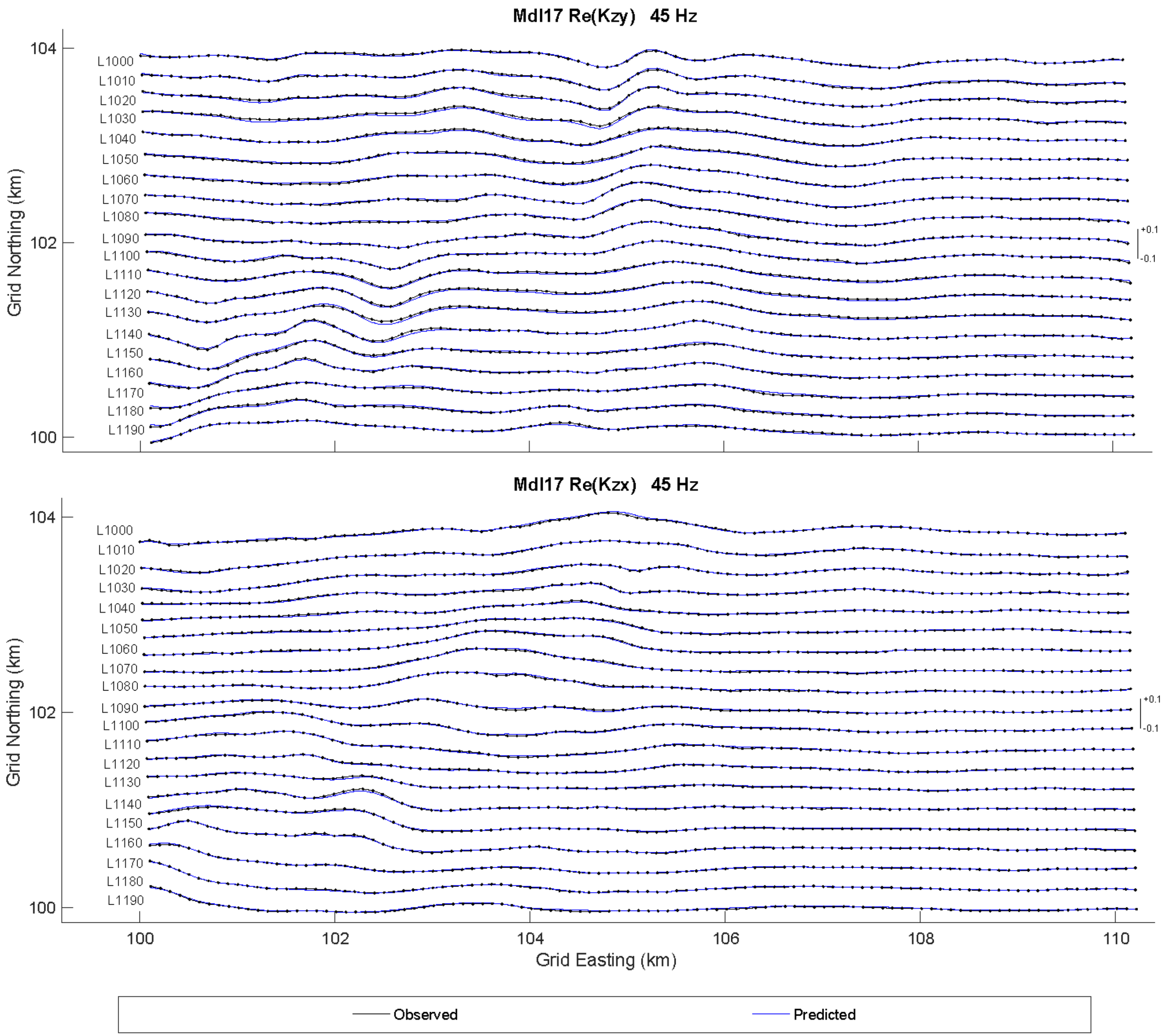
Eleven Mile Canyon 3D ZTEM (Only) Inversion

- 2040 ZTEM stations: 20 flight profiles, 200 m sep., 100 m data intervals 360 Hz – 30 Hz
- Mesh: 117 (x) x 261 (y) x 40 (z) nodes, 13 air layers; bird heights (62 – 179 m) included
- 100 ohm-m starting model, ZTEM data error floor of 0.01, ~5 hrs/iter. on 24 core w/s
- Good algorithm convergence to nRMS of ~0.5
- Possible hydrothermal clay cap in west-central portion of study area
- Transition from outcrop to valley alluvium from west to east



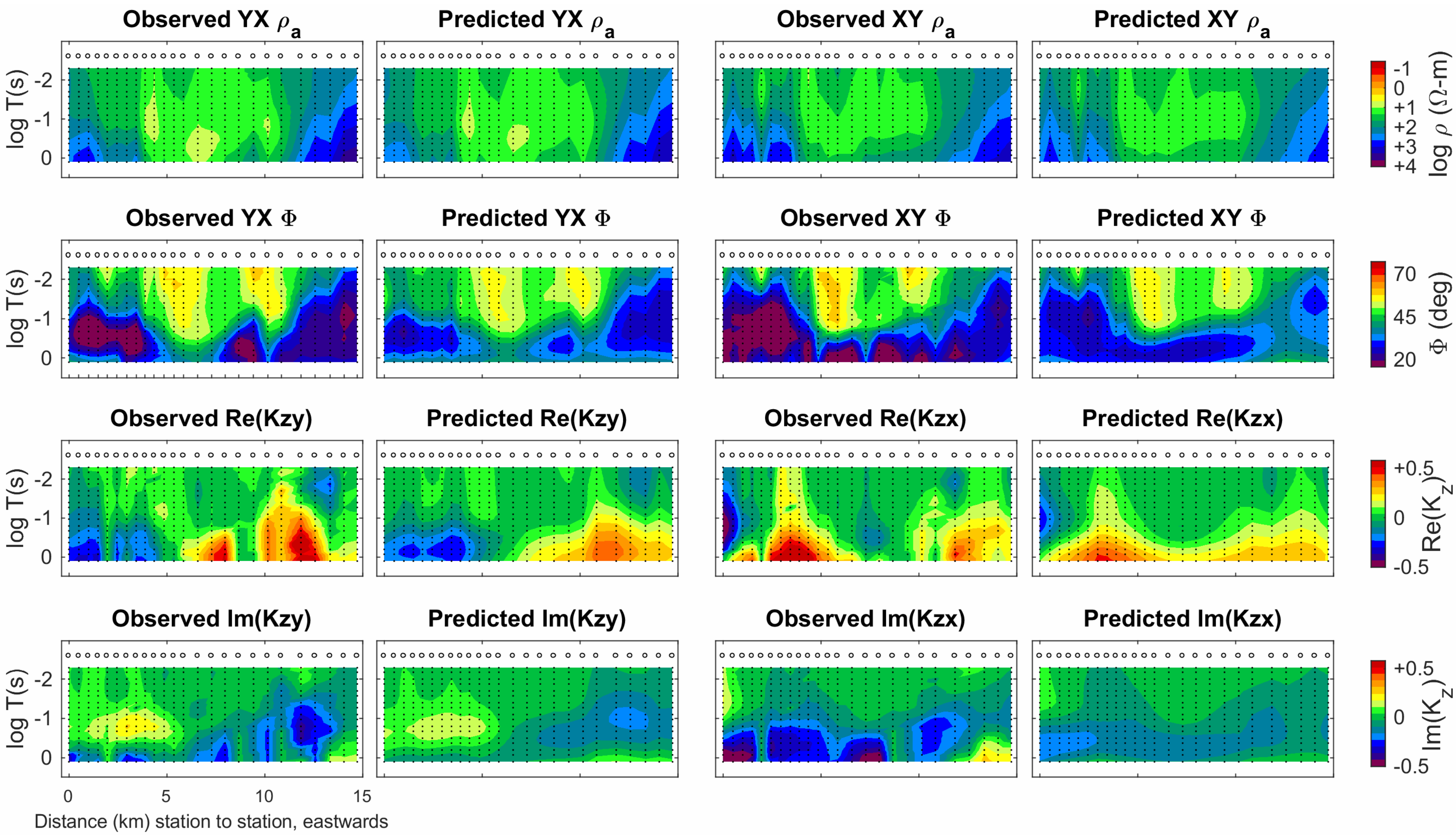
Eleven Mile Canyon 3D ZTEM/MT Joint Inversion

- 25 station MT profile onlapping from the east: 200 – 0.78 Hz, 10% Z_{ivr} error floor
- Good algorithm convergence to nRMS of <1. for both ZTEM and MT
- Possible hydrothermal clay cap preserved, detailed.
- Valley graben alluvium much more clearly defined



Example fit of 3D ZTEM (Only) Inversion
Model to Observations at 11 Mi Cyn

Methods/Approach



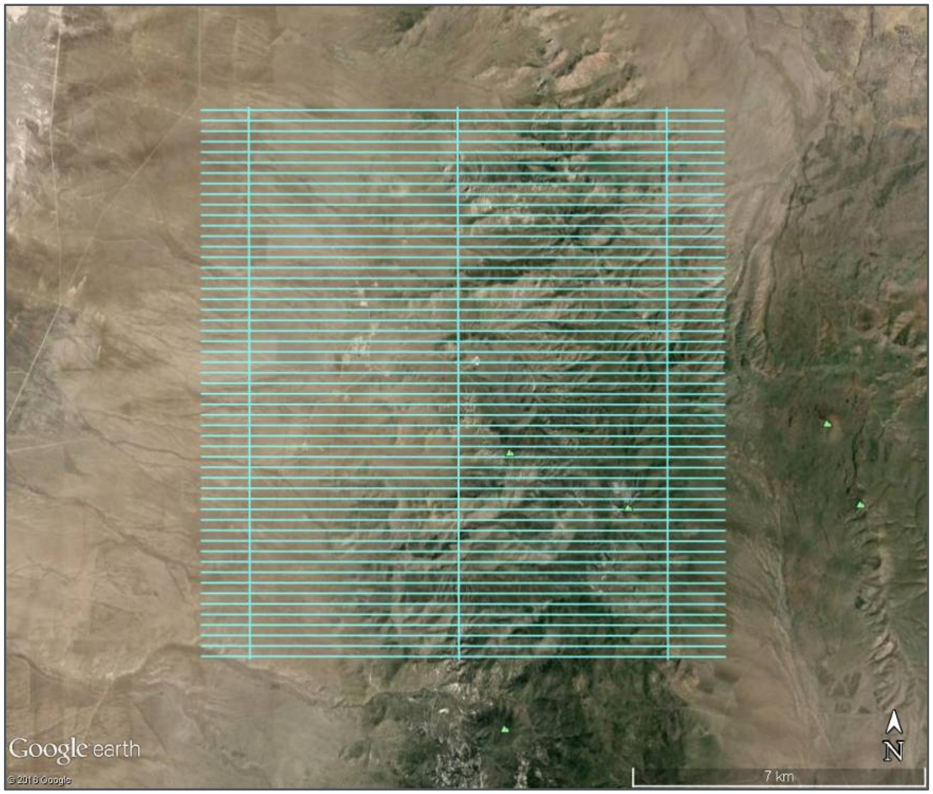
Pseudosections of MT Profile Observations and Model Predictions
For Eleven Mile Canyon ZTEM/MT Joint 3D Inversion

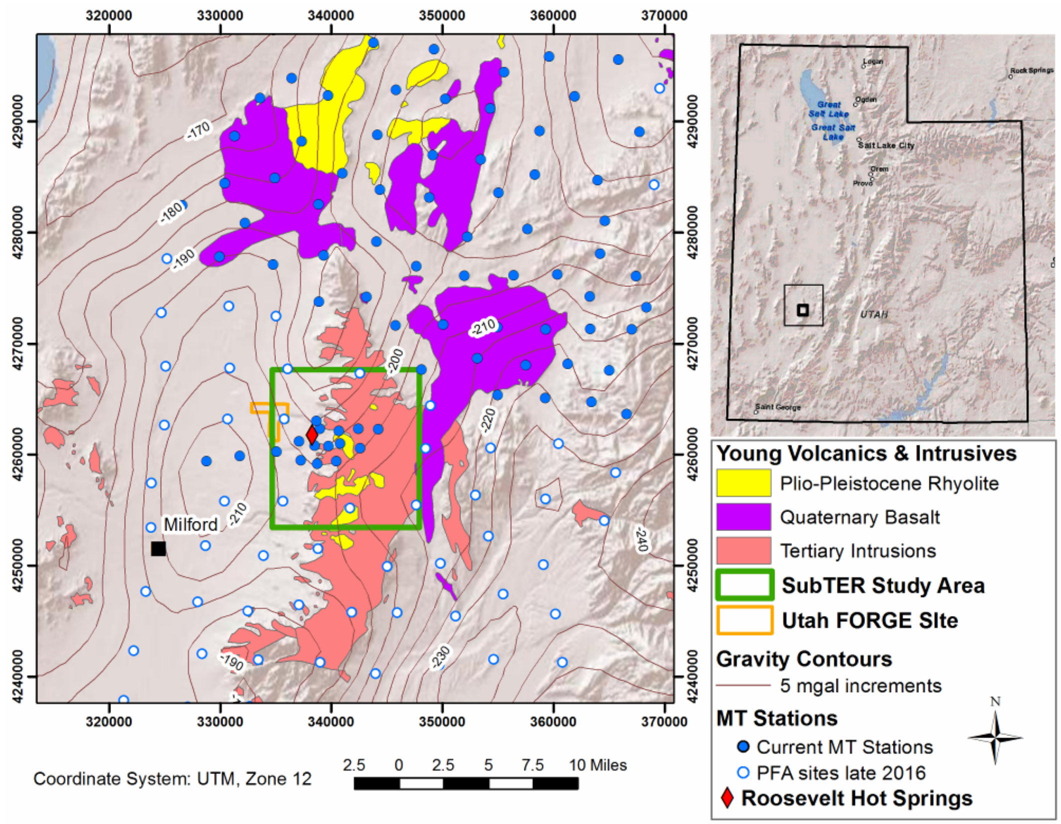
Methods/Approach

Technical Accomplishments and Progress

- Project concept of joint ZTEM/MT data collection and inversion affirmed as viable research direction.
- Major field surveys over RHS and central MMts completed as planned within budget.
- Direction established for advanced ZTEM response processing using jackknifing.
- Joint 3D inversion algorithm exercised on separate data set (Eleven Mile Canyon, NV).

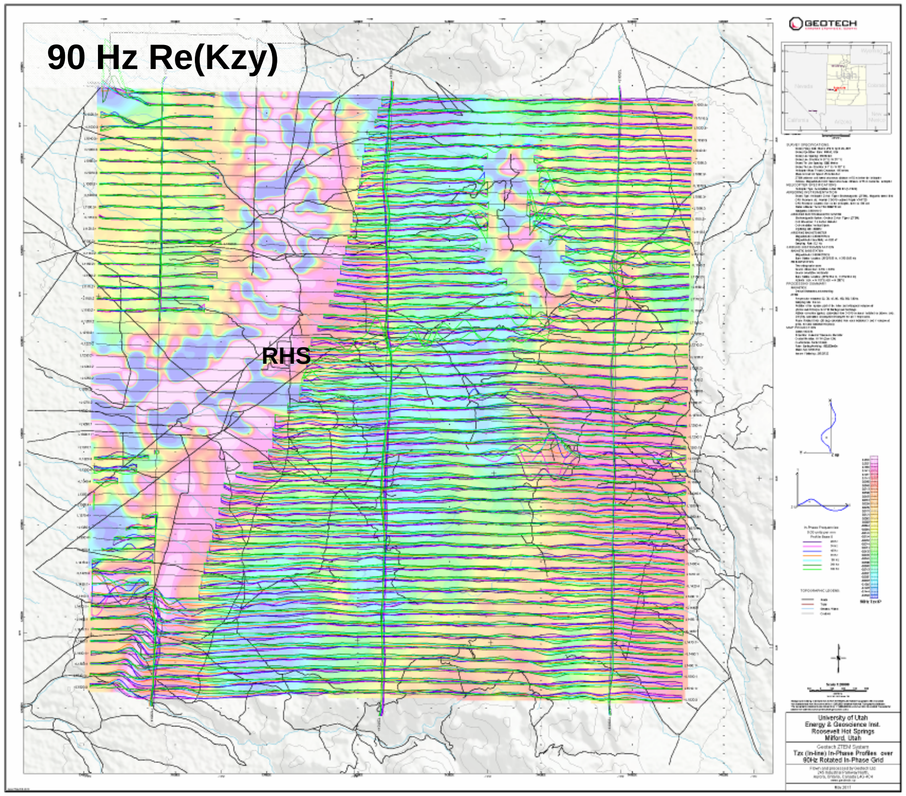
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Contract emplacement, scheduling among subcontracts	Achieved Original	Oct. 2016
ZTEM survey intended for RHS plant maintenance shutdown	Achieved Original	Apr. 2017
Advanced ZTEM data processing via jackknife outlier removal	Determination of approach to estimate higher-order jackknife function	Sep. 2017
Detailed MT survey over RHS and central MMts	Achieved Original	Oct. 2017
3D separate and joint inversion of RHS/MMts ZTEM/MT survey	Year 2 Activity	pending
Updated geological geothermal model of RHS and central MMts	Year 2 Activity	pending

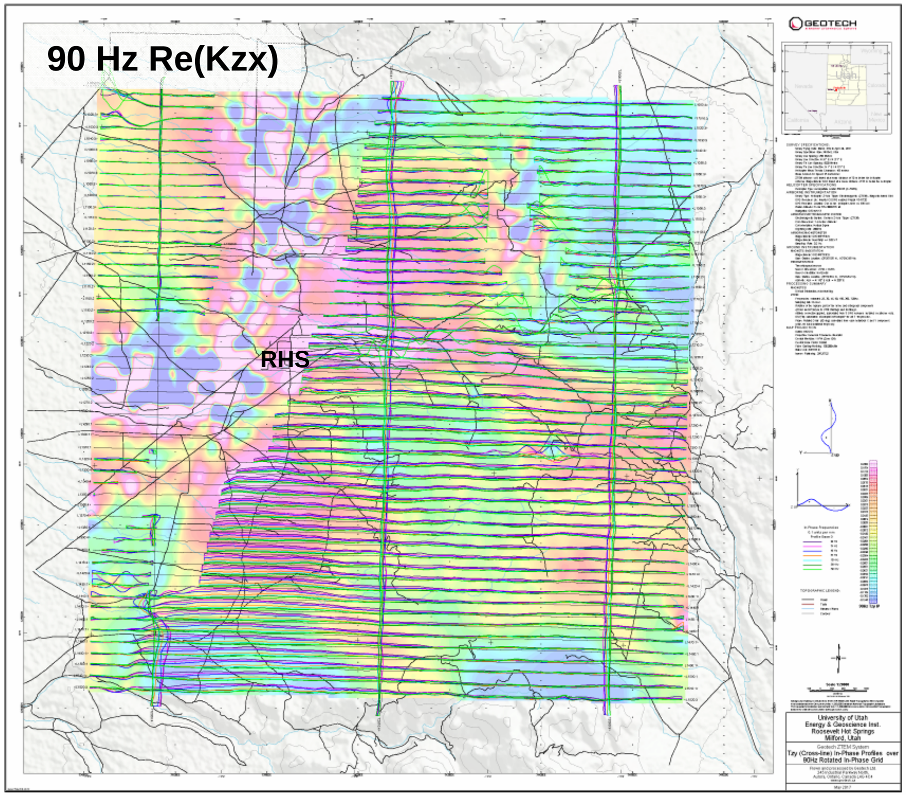




ZTEM airborne EM Survey, RHS and central MMts

- Proposed line coverage of 704 km achieved
- Slight deviation at NW corner due to windmill physical structures
- Sferic signal high, steady weather allowed good topo draping





<u>ZTEM airborne EM Survey, RHS and central MMts</u>

• Generally good quality signal down to 22 Hz

• Some power line (PL) interference toward NW due largely to RMP 345 kV Tx line; areas east of RHS generally clean

• Kern R gas pipeline manifest in SW corner running N along PL corridor

Jackknife Response Processing

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n}\bar{x}_i.$$

Simple Mean Response Estimate

$$\bar{x}_i = \frac{1}{n-1}\sum_{j=1, j\neq i}^{n} x_j, \qquad i = 1, \ldots, n.$$

N Delete-one Response Estimates

$$\mathrm{Var}(\bar{x}) = \frac{n-1}{n}\sum_{i=1}^{n}(\bar{x}_i - \bar{x})^2.$$

N Delete-one Response Variances

- Iterate Delete-one estimates until variance is minimized.
- Can also estimate mean and slope of linear function through jackknife estimation.
- Will apply this to minimal time interval mini-responses to improve 22 Hz and attain 15 Hz.

Technical Accomplishments and Progress

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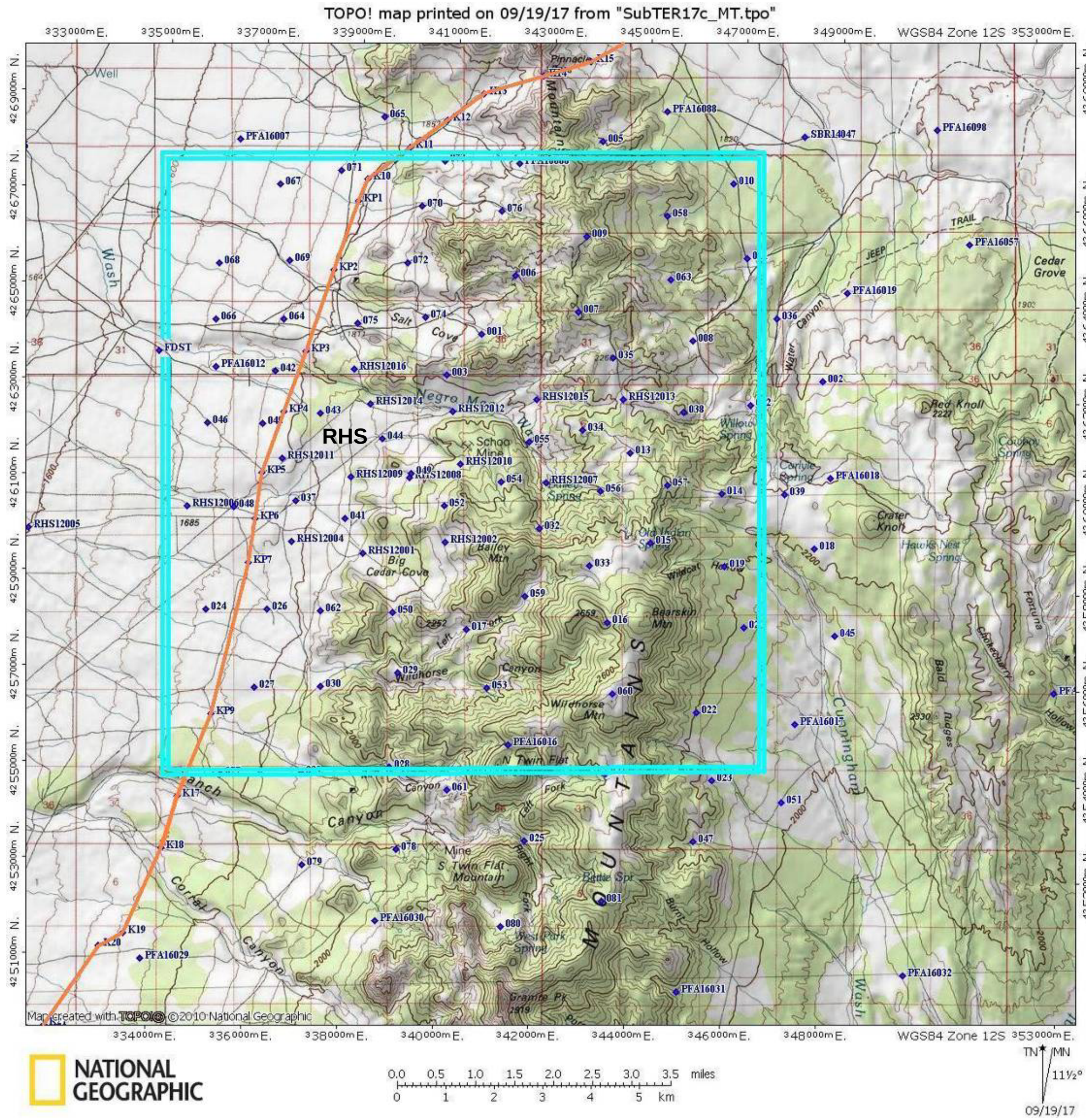
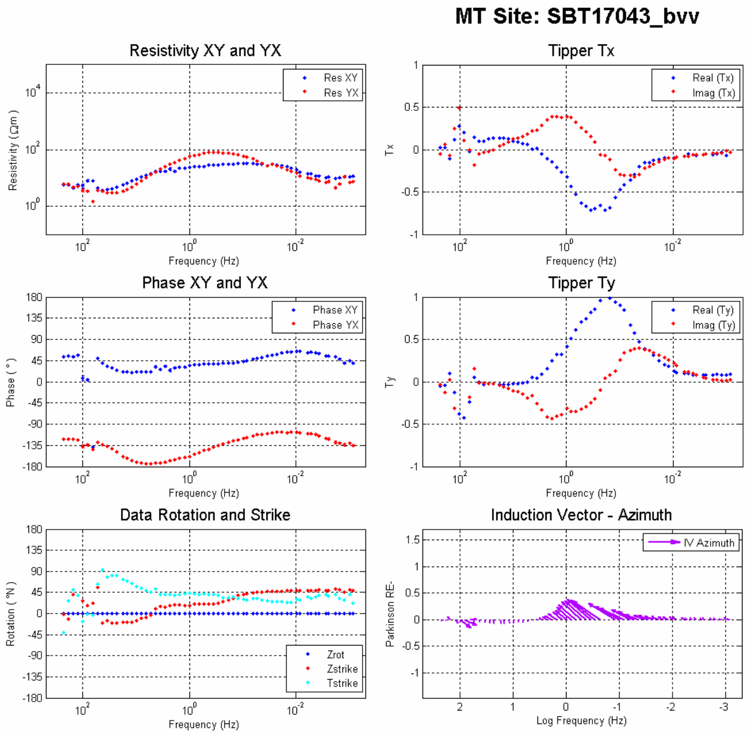


Ground MT Survey, RHS and central MMts

- 80 stations completed early October.
- Due to 15 hrs streaming recording, quality good even ~250 m from RHS.
- Kern R pipeline to be explicitly modeled.



Research Collaboration and Technology Transfer

- Project integrates industry state-of-the-art airborne and ground EM surveying technology (Geotech Inc., Quantec Geoscience) with advanced response processing and 3D inversion method (University of Utah/EGI).
- Several students and post-doc funded under the project.
- Long-standing data acquisition and processing relationship with subcontractor Quantec Geoscience.
- PI Wannamaker advises subcontractors on field setup (e.g., ultra-remote referencing) and response processing in areas of widespread cultural/industrial EM interference.
- Progress will results presented multiple times per year at geothermal/exploration conferences attended by industry, academia and national labs.

Future Directions

- Take final delivery of processed MT responses, final debrief with ZTEM contractor.
- Upgrade quality of ZTEM responses through jackknife outlier removal and attempt to reduce powerline influence.
- Joint and separate imaging analysis using finite element platform, assessment of efficiencies by replacing MT sites with ZTEM coverage.

Year 2 Milestone or Go/No-Go	Status & Expected Completion Date
1. Project management	Ongoing, Proposed plan current, Sep. 2018
3b. Advanced ZTEM response processing	Jackknifing order defined; Mar. 2018
4. Delivery of processed MT responses	Field work complete; Nov. 2017
5. Separate and joint ZTEM/MT inversion	Upcoming; Jun 2018
6. RHS/MMts Geologic Model Update	Upcoming; Sep. 2018

Summary

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- Airborne EM coverage has promise of improving sampling of geothermal resistivity and reducing logistical challenges.
- Non-uniqueness of airborne-only data must be reduced with finite amount of MT sounding data, but could be savings nonetheless.
- Efforts being made to improve low frequency data via jackknife outlier removal.
- The power of joint data set collection is realized with recent 3D inversion development that includes potential steep topography.
- Intention at RHS/MMts is to reveal preferred orientations of basement fracture sets plus deep heat sources related to production or Quaternary rhyolite volcanism.