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

Fracture Network and Fluid Flow Imaging for EGS Applications from Multi-Dimensional Electrical Resistivity Structure

May 18, 2010

Principal Investigator:
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University of Utah
Energy & Geoscience Institute

Overview Slide

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- Project Context:
  - Timeline
    - Project start date: January 6, 2010
    - Project end date: January 6, 2013
    - Percent complete: 5%
  - Budget
    - Total project funding: $699,863
    - DOE share: $559,485
    - Awardee share: $140,378
    - Funding for PY10 (total): 244,331
  - Barriers
    - Lack of available and reliable resource information
    - High exploration risks
    - Inadequate site selection, characterization, resource assessment
  - Partners
    - ENEL North America (ENA) Ltd. (informal)
    - Virginie Maris (Post-Doctoral Scholar, beginning June)
    - Michal Kordy (Ph.D Student, arriving August)

Relevance/Impact of Research

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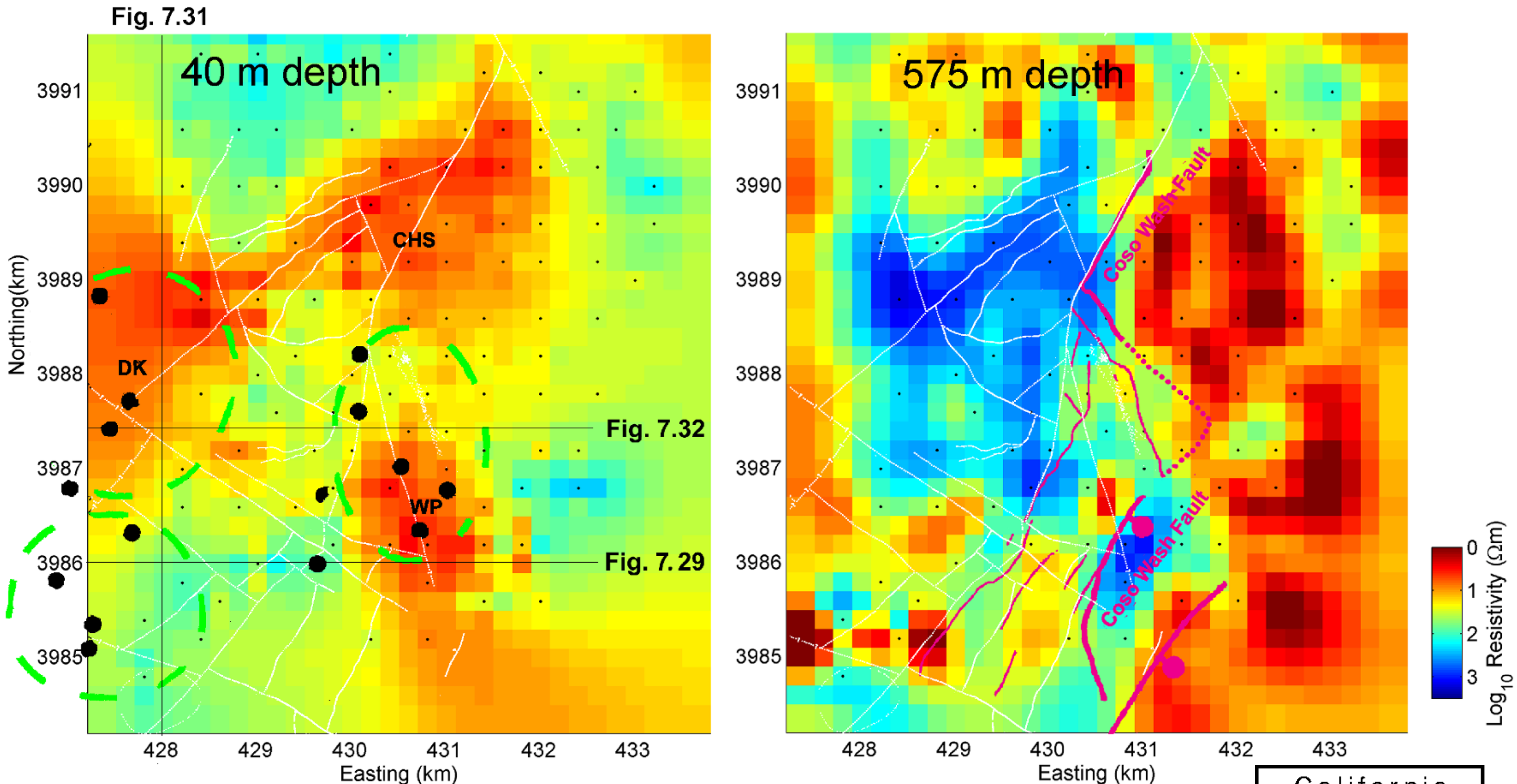
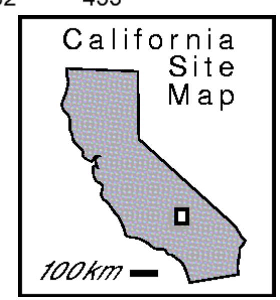
Versatility and Efficiency in Imaging Fluid Flow via Electrical Resistivity

- 1), Develop a 3-D code for simulating EM responses at the surface of the earth with topographic variations. To start, two platform choices will be pursued to determine the superior approach.
- 2), Incorporate the selected simulation code and the inversion parameter jacobians that follow from it into an existing inversion algorithm for imaging and monitoring and improve its efficiency.
- 3), Parallelize the inversion code on new-generation multi-core workstations to achieve fast calculations within a single, cost-efficient, shared memory processing (SMP) box.
- 4), Apply the final algorithm to two important geothermal field MT data sets, one from an extensional system and one from an andesitic system.

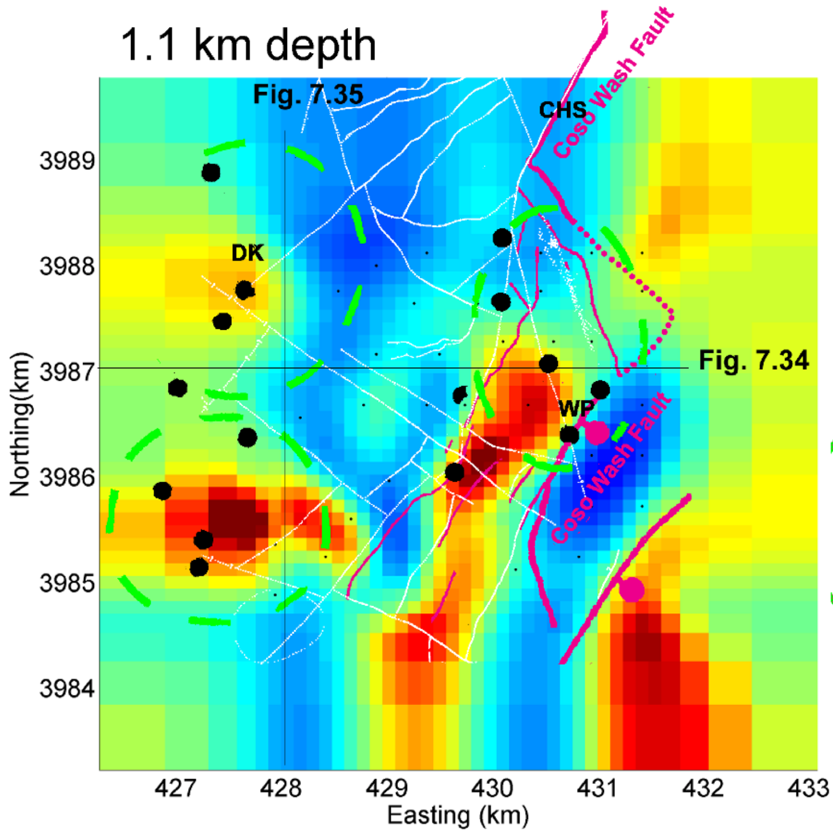
Relevance/Impact of Research

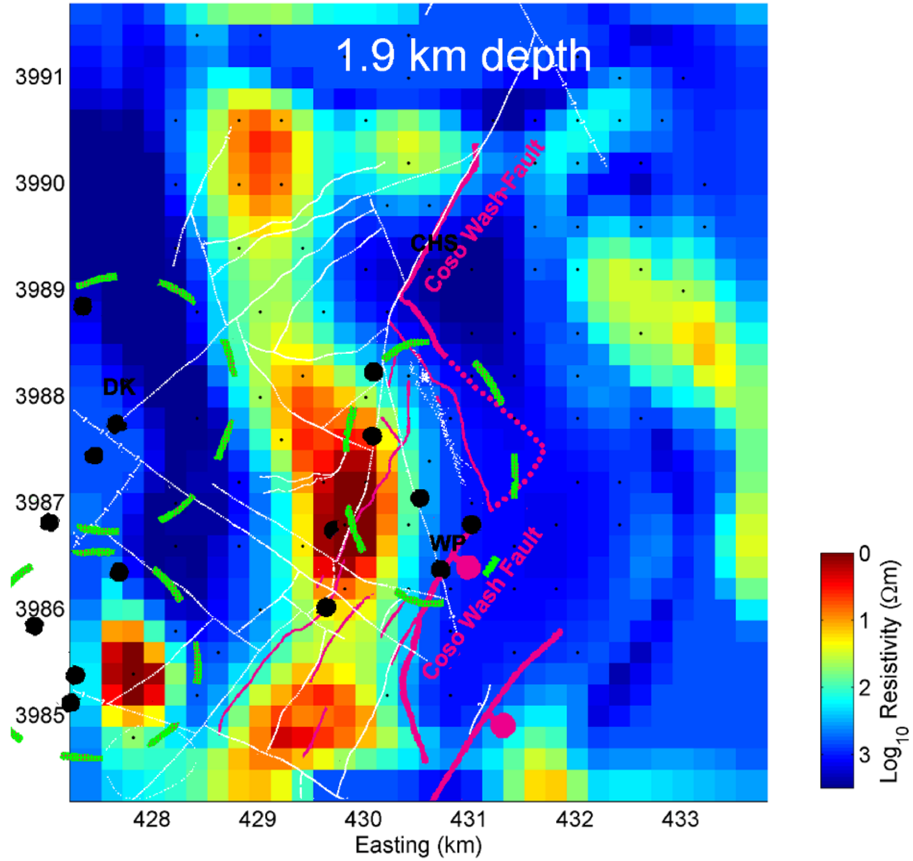




Coso Geothermal Field, California
3-D Inversion Slices, East Flank MT Survey
(Maris, in prep.)

Relevance/Impact of Research





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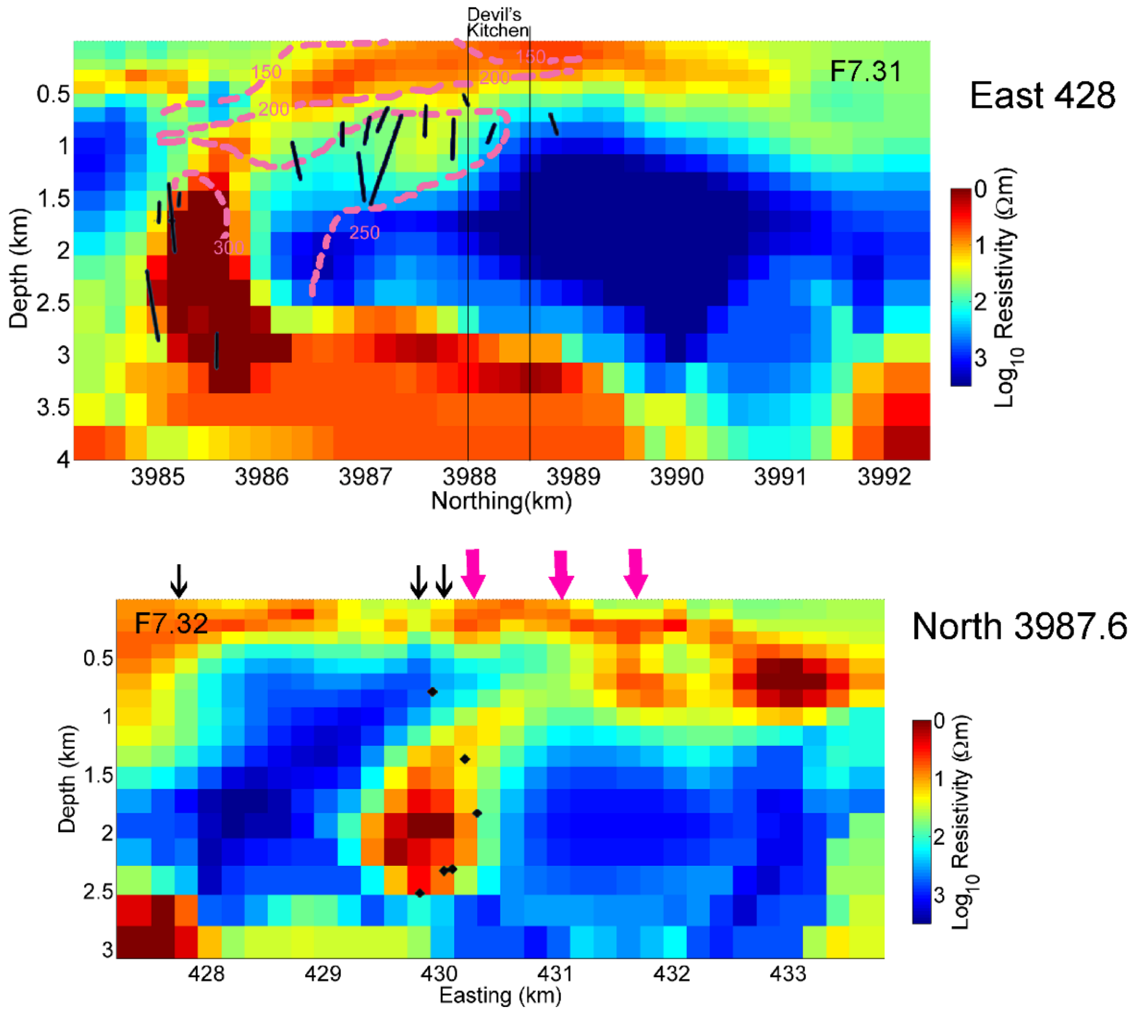
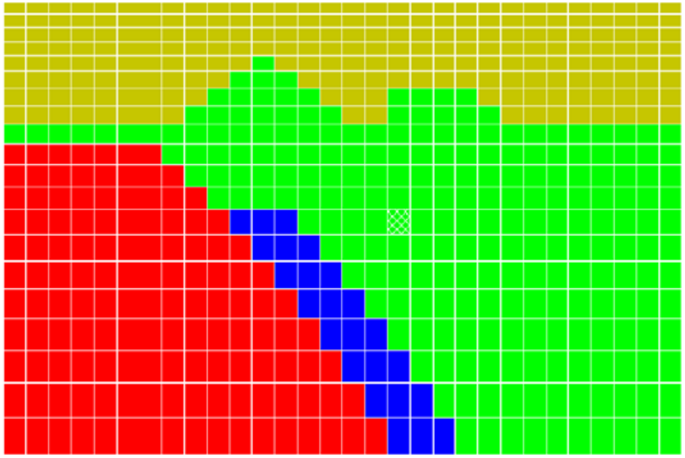


Inversion slices compared to production/lost circ (Maris, in prep.)
(production/lost circ redrawn after Newman et al., 2008;
temperature contours after Adams et al., 2000)

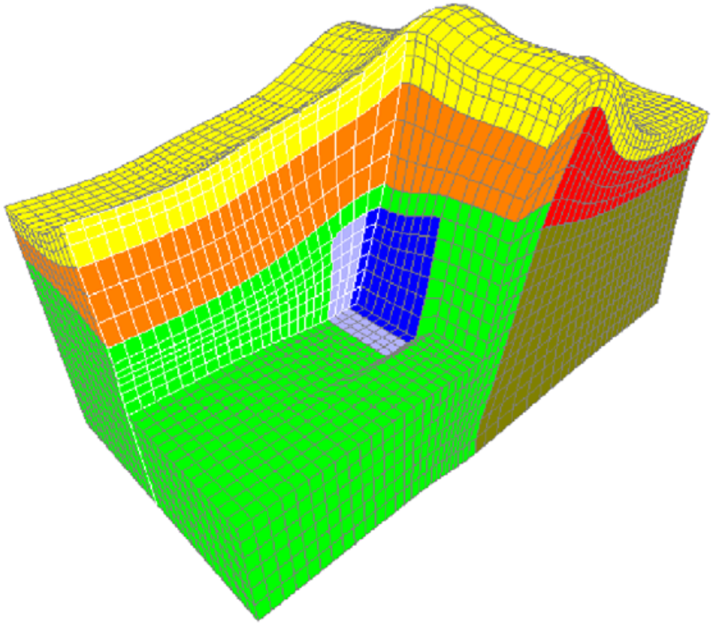
Electromagnetic Simulation and Inversion with Conformal Receiver Surfaces (Topography)



Finite Difference Topo Model

MT3DI

Madden et al., Newman et al., Siripunvaraporn et al., Sasaki



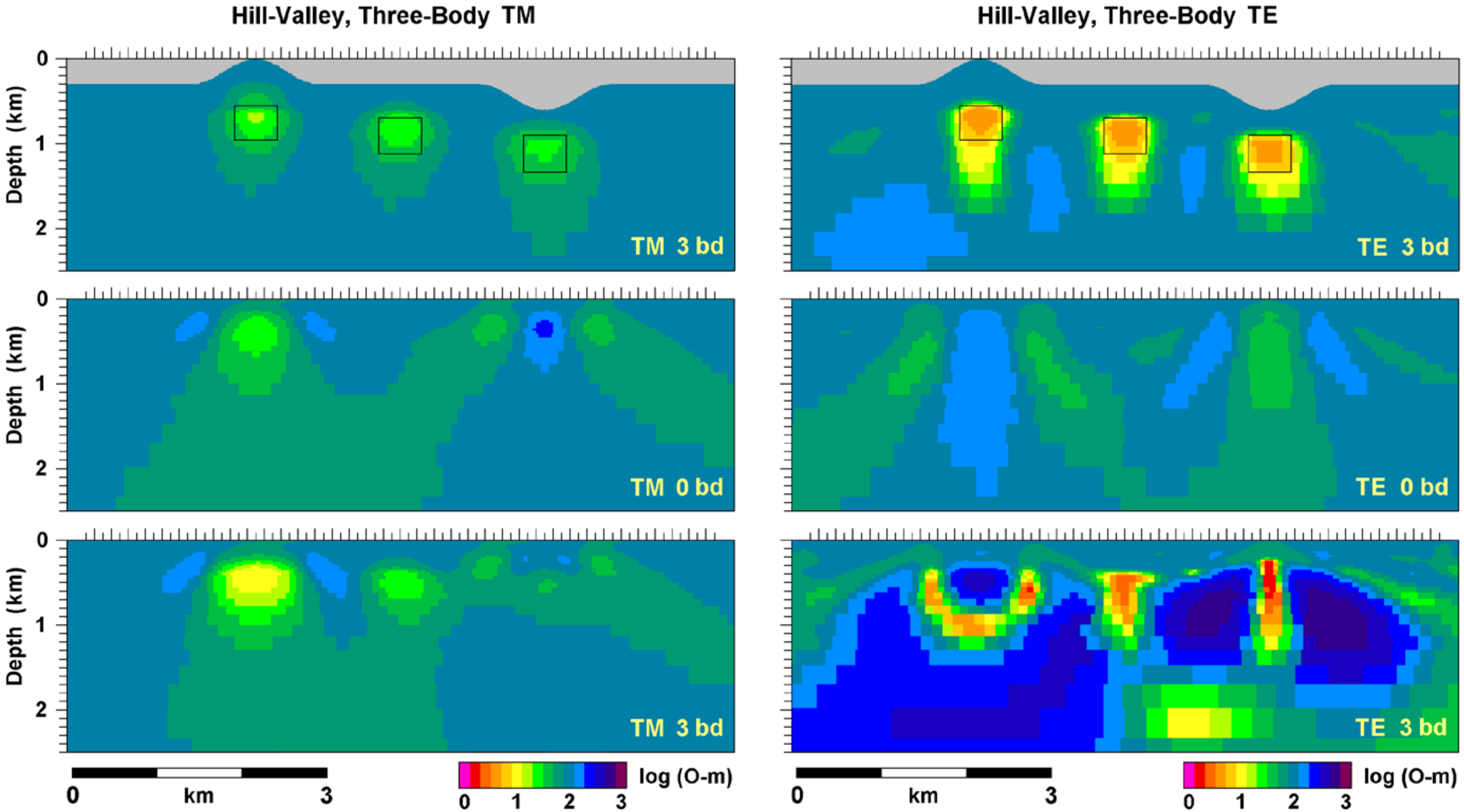
Deformable Mesh Cutout View

Loki-3D

Sugeng, Wilson, Annetts, Raiche

Graphics after Art Raiche

Influence of Topography/Errors When Ignored



Evaluate Two Independent Approaches

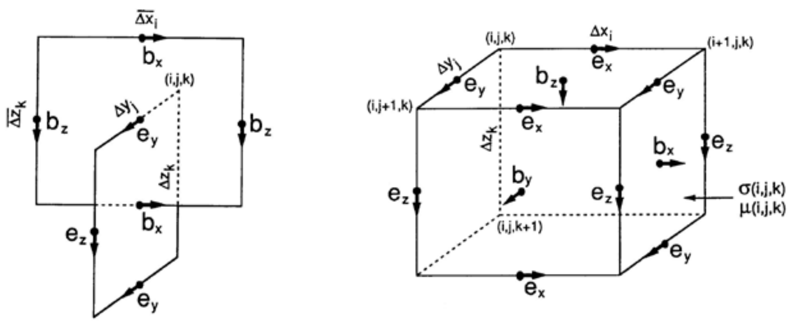
Select Superior Approach for Further Development

$$\oint H \cdot ds = \iint \sigma E \cdot ds$$

$$\oint E \cdot ds = \iint \mu\omega H \cdot ds$$

e.g.,

$$(E_{xt} - E_{xb})/\Delta z - (E_{zr} - E_{zl})/\Delta x = i\omega\mu H_{yc}$$

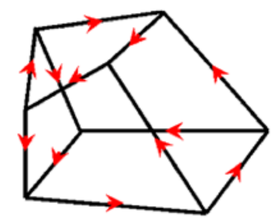


$$\nabla \times \nabla \times \mathbf{E}^e + k^2\,\mathbf{E}^e = -i\omega\mu\,\mathbf{J}_0^e$$

$$\mathbf{E} = -i\omega\mu\,\mathbf{F} + \frac{1}{\sigma}\nabla\nabla \bullet \mathbf{F} \qquad \mathbf{H} = \nabla \times \mathbf{F}$$

$$\nabla^2\mathbf{F} - k^2\mathbf{F} = -\mathbf{J}_0^e$$

$$\mathbf{F}_k = \sum_{i=1}^{edges} \mathbf{N}_i e_{i,k}$$



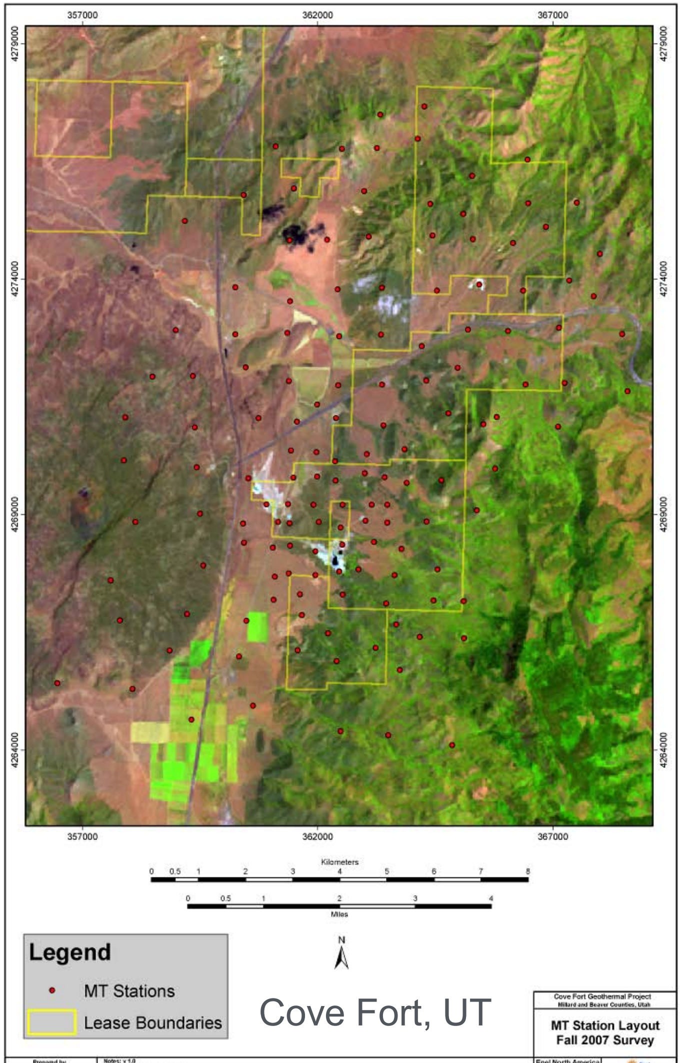
Finite Difference Staggered Grid

- Difference eq'ns originated from integral forms of Maxwell's eq'ns
- Generalize to cell vertex positions from heights, widths

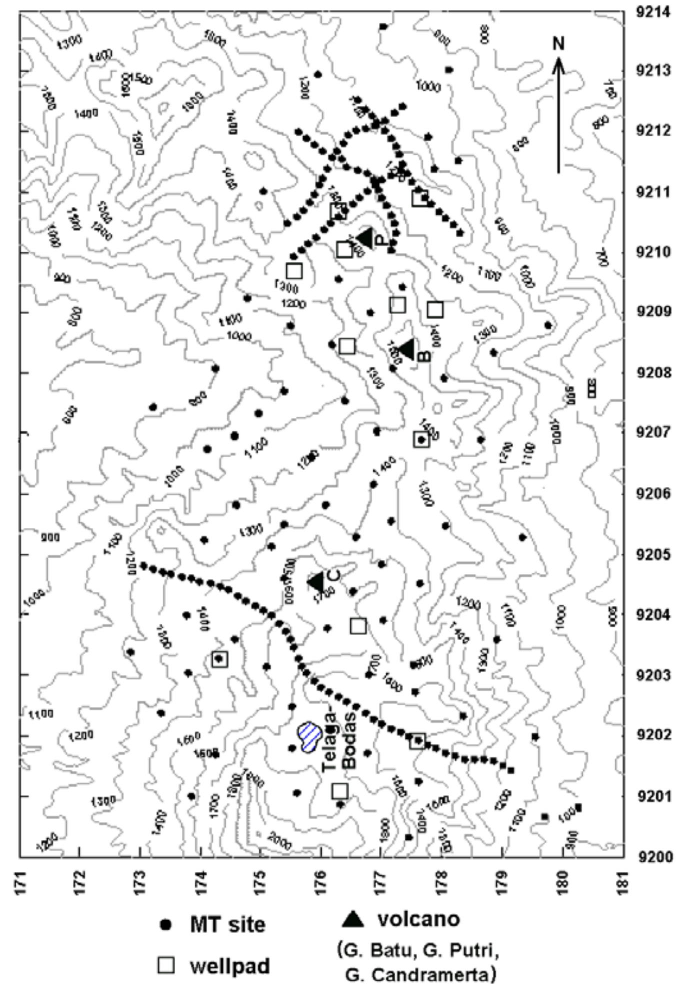
Finite Element Deformable Mesh

- Topography already incorporated
- Only solves for H at present
- Need to derive E through double spatial derivatives

Scientific/Technical Approach



(~800 m elevation change)



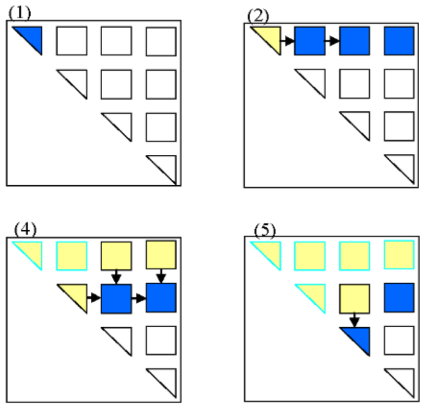
Karaha, Java, Indonesia
(~1000 m elevation change)

Multi-Core Workstation Parallelization of 3D FD MT Inversion

(Maris and Wannamaker, 2010, C&G, in press)

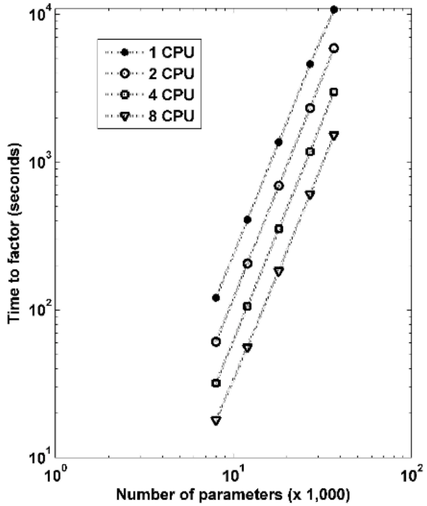
Modified Cholesky Parameter Step

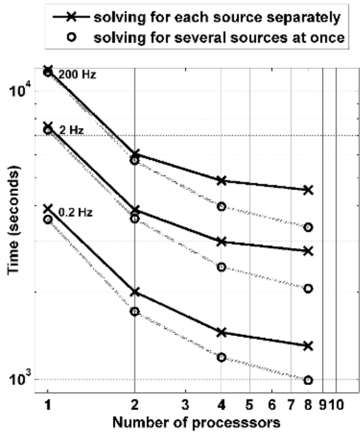
(Excellent Scalability, Preserves N^3 ops.)



Paul Otellini, CEO Intel, holds 80-core chip wafer (PBS News Hour archive)

Dual quad-core
Xeon 5355 2.66 GHz
16 GiB RAM





Bi-conjugate Gradient Forward, Jacobians

(Likely limited by processor-RAM bus speeds)

Accomplishments, Expected Outcomes and Progress

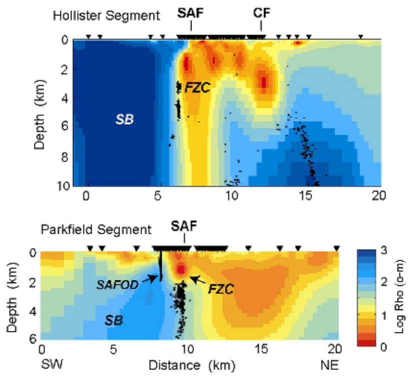
Initial Efforts:

- Obtained Loki-3D algorithm, reviewed code structure with developer Dr. Glenn Wilson, compiled and ran test examples.
- Completed publication, now in press, on parallelization of inversion code on multi-core, single-box workstations.
- Continued exercising limits of existing inversion code at workstation level using Coso MT data set.
- Investigated relationship between seismicity and resistivity structure while concluding Ph.D thesis research of Maris.

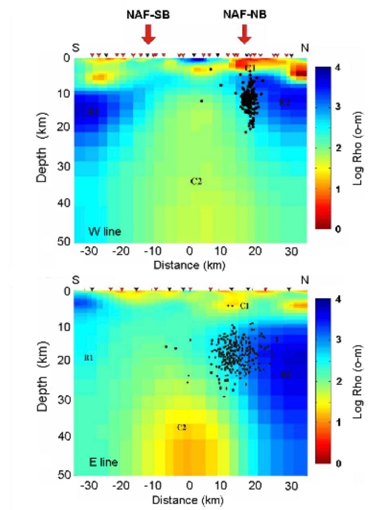
Plans:

- Incorporation of plane-wave sources into Loki-3D, verification of magnetic field responses.
- Experiment with various interpolation approaches for spatial derivatives to yield the electric field.
- Generalize finite difference equations for arbitrary prism geometries based upon integral forms of Maxwell's equations.
- Select superior forward problem module for inversion platform development.

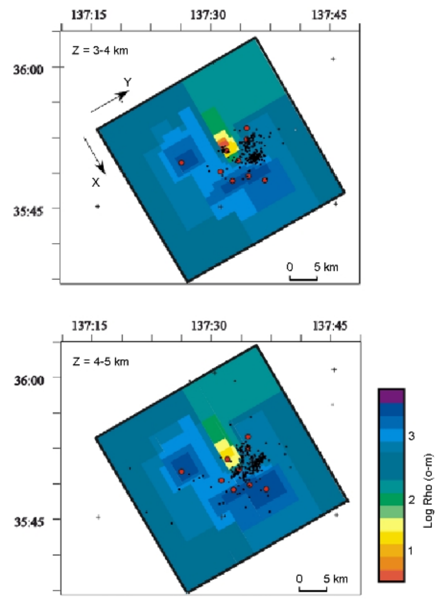
Accomplishments, Expected Outcomes and Progress



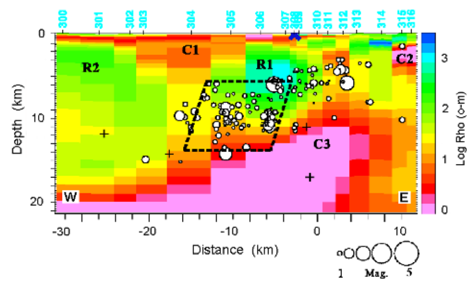
San Andreas: Bedrosian et al., Tectonophys., 2004



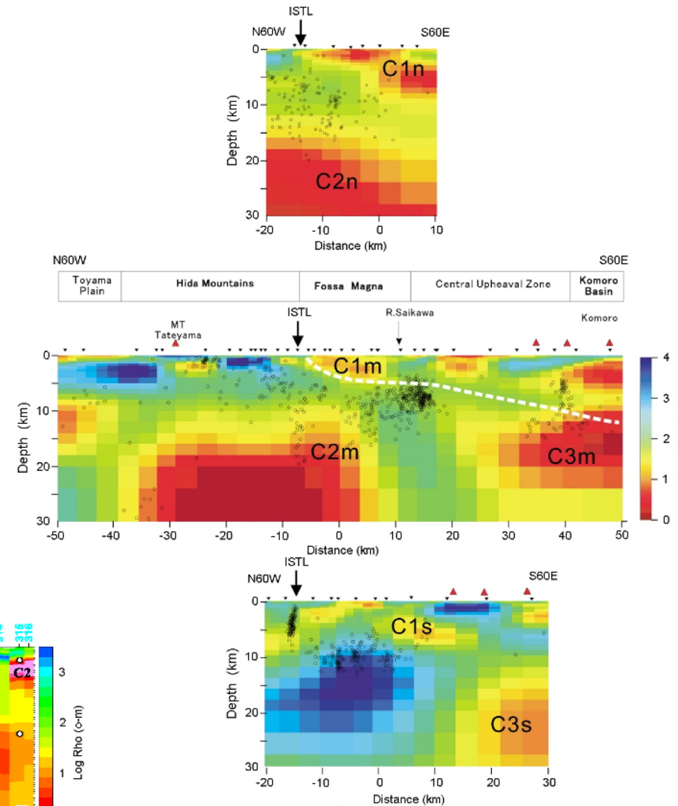
North Anatolian: Tank et al., PEPI, 2004



Nagano: Kasaya and Oshiman, EPS, 2004



Miyagi: Mitsuhata et al., GRL, 2001



Itoigawa-Shizuoka: Ogawa and Honkura, EPS, 2004

Seismicity tends to cluster along conductor-resistor margins.
Fluidized conductive zones are soft, don’t support stress.
Conductive zones can provide fluids to trigger eq’s in resistors.

Accomplishments, Expected Outcomes and Progress

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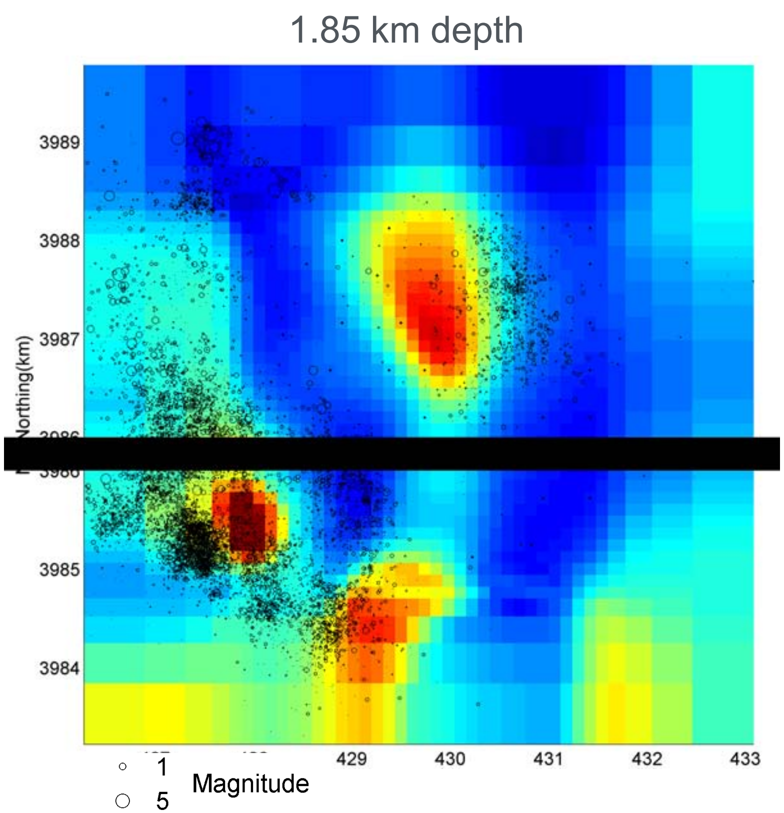

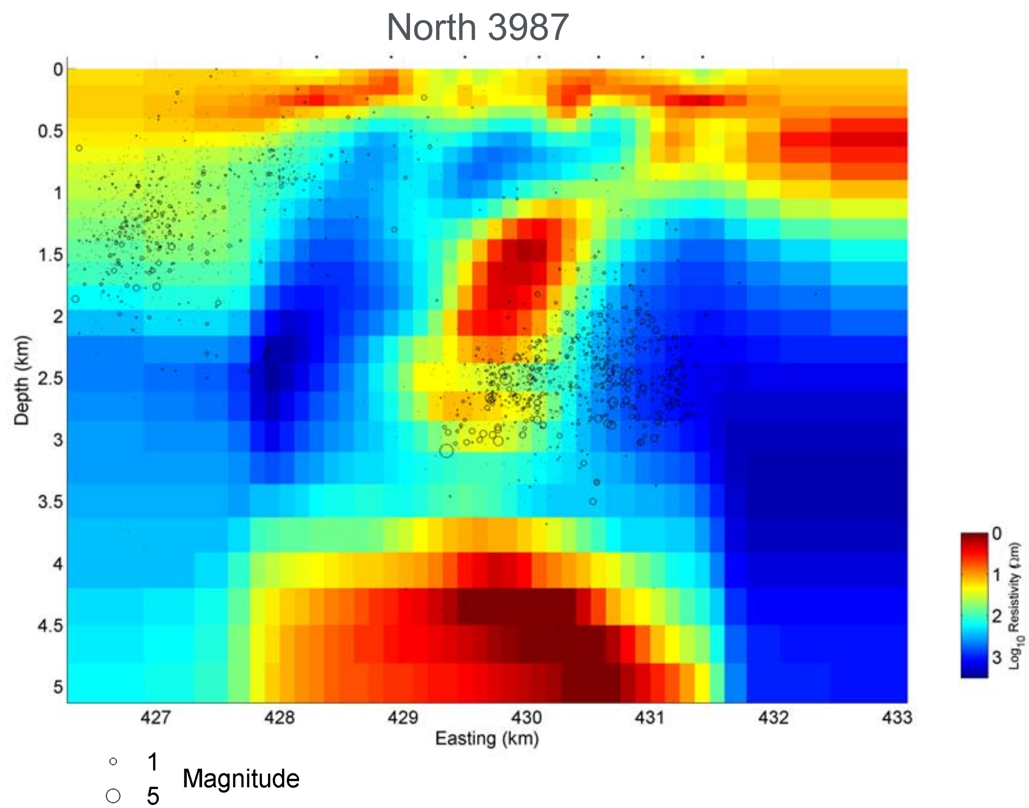

Model slices with seismicity overlay (Maris, in prep.).
Coso seismicity provided by B. Julian for 1997-2007.
Correlation between seismicity and conductor margins good.

Project Management/Coordination

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Table 1. Time Line of Research Tasks

Project Year Defined According to Project Start Date

Activity Interval as Fraction of total P.I. Support

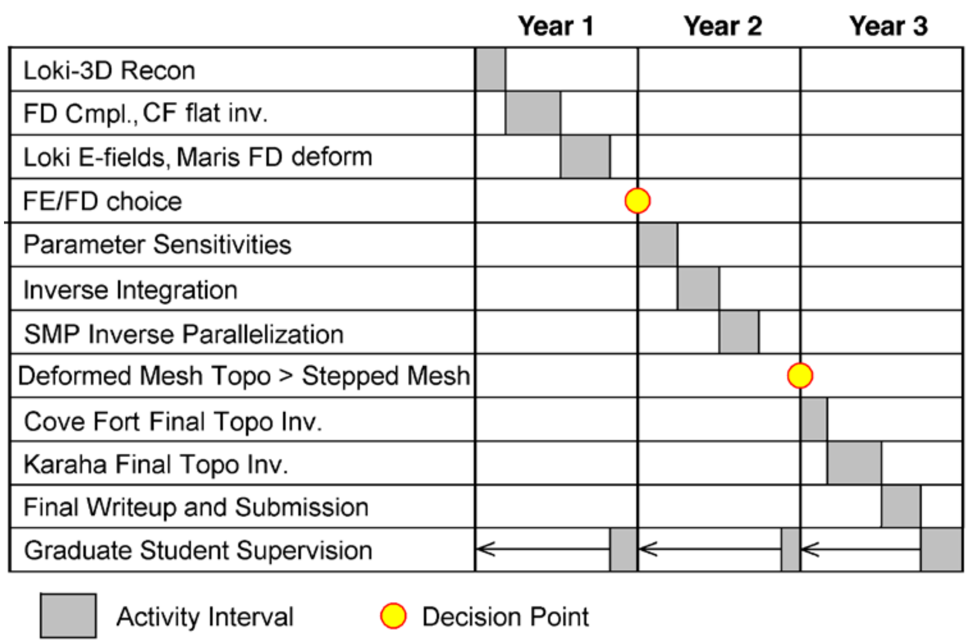


Table 2. Cost Profile for Project Tasks

Project Year Defined According to Start Date

Loki-3D Recon	$56,083	Year 1
FD Cmpl., CF flat inv.	$93,471	
Loki E-fields, Maris FD, w/s purch.	$94,777	
Year 1 Total	$244,331	
Parameter Sensitivities	$92,528	Year 2
Inverse Integration	$92,528	
SMP Inverse Parallelization	$37,011	
Year 2 Total	$222,067	
Cove Fort Final Topo Inv.	$77,822	Year 3
Karaha Final Topo Inv.	$58,366	
Final Writeup and Submission	$97,277	
Year 3 Total	$233,465	
Total for Project	$699,863	

1. 3-D Forward Problem Development
2. Inverse Integration/Parallelization
3. Post-Doc/Grad Student Supervision
4. Inversion of Geothermal Data Sets

Future Directions

- PY10: Augmentation of the Loki-3D algorithm for plane-wave source H-fields, test interpolation schemes for E-field, verify topography. Embark on generalizing finite difference platform for deformable mesh cells, verify topography.
- PY11: Decision point- Choice of superior forward platform for topographic simulation. Installation of jacobians into chosen platform, initial inverse testing. Parallelization of inverse on multi-core workstation.

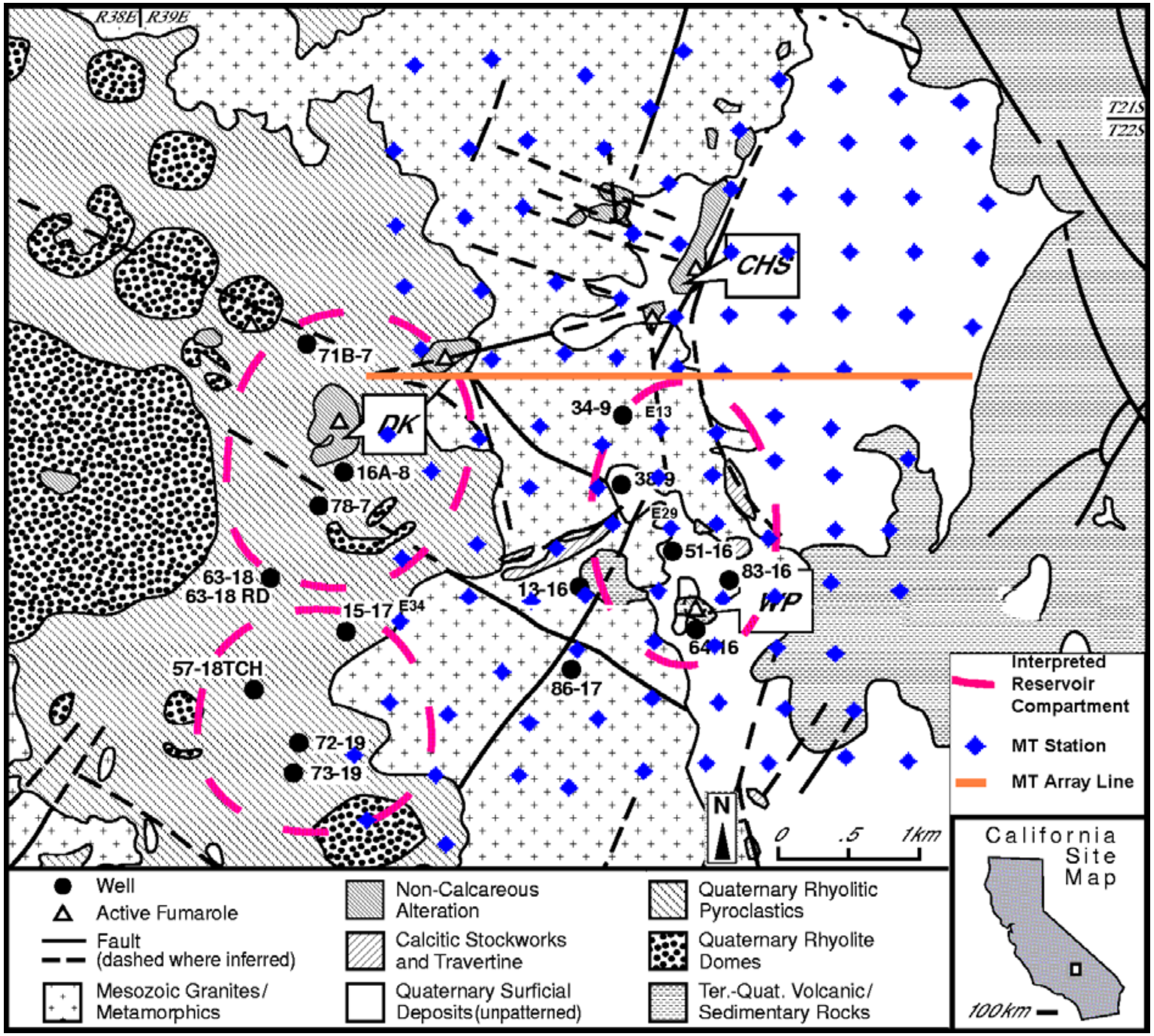
Summary Slide

- Electrical resistivity emerging as key indicator of physical state, fluid distributions in geothermal systems.
- MT is the method of choice for depths beyond 1-2 km.
- Image accuracy with rugged terrains requires explicit accounting of receiver x-y-z distributions.
- Useful inversion capability affordable by many is becoming possible with multi-core architectures.
- Need to train young professionals to achieve state-of-the-art, and beyond.

Publications Receiving Support from this Grant:

- Maris, V., and P. E. Wannamaker, Parallelizing a 3D Finite Difference MT Inversion Algorithm on a Multicore PC using OpenMP: Computers & Geosciences, in press, 2010.
- Maris, V., Parallelized Three-Dimensional Inversion of MT Data from the Coso Geothermal Field, on a Multi-Core Computer: Ph.D. dissertation, University of Utah, expected defense date May, 2010.

Optional Slide 2



Coso California Geothermal Field, MT Station Map