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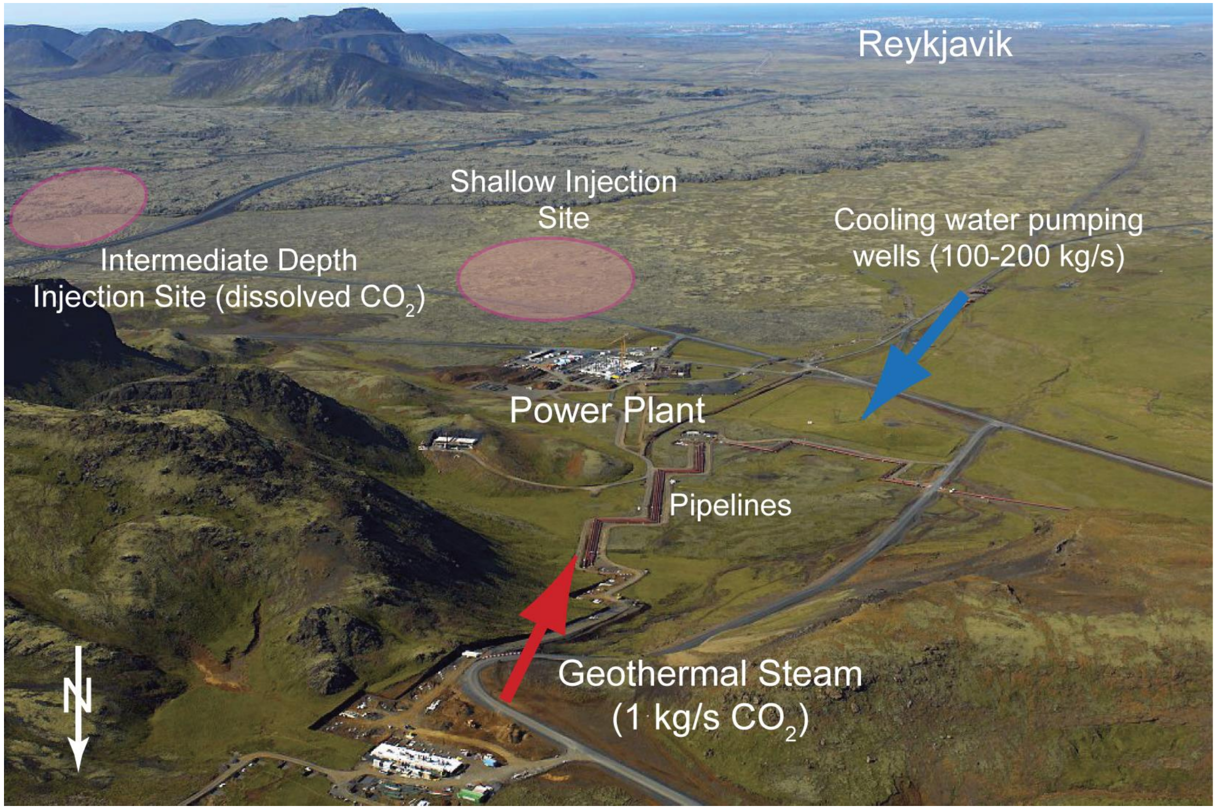


# Advanced 3D Geophysical Imaging Technologies for Geothermal Resource Characterization

May 11-14, 2015

**Principal Investigator: Greg Newman, Michael Fehler**

**Organizations: LBL & MIT**

Track Name: Exploration Validation / Play Fairway Analysis

# Collaborators

## Project Participants and Collaborators:

Lawrence Berkeley National Laboratory
Massachusetts Institute of Technology
Iceland GeoSurvey (ÍSOR);
Reykjavík University;
Uppsala University;
TerraGen (Operator of the Coso Field);
Icelandic Power Companies

*Funded as comprehensive Icelandic/USA cooperative project under the International Partnership for Geothermal Technology (IPGT) agreement*

## Project objectives

- Develop improved geophysical imaging methods
  - characterizing subsurface structure
  - identify fluid locations
  - characterize fractures
- Obtain the maximum amount of information from seismic and electromagnetic data:
  - 1) Seek improvements to baseline imaging methods
  - 2) Developing new joint inversion methodologies
- Improve methods by application to real data from four systems
- Demonstrate applicability of methods

# Scientific/Technical Approach

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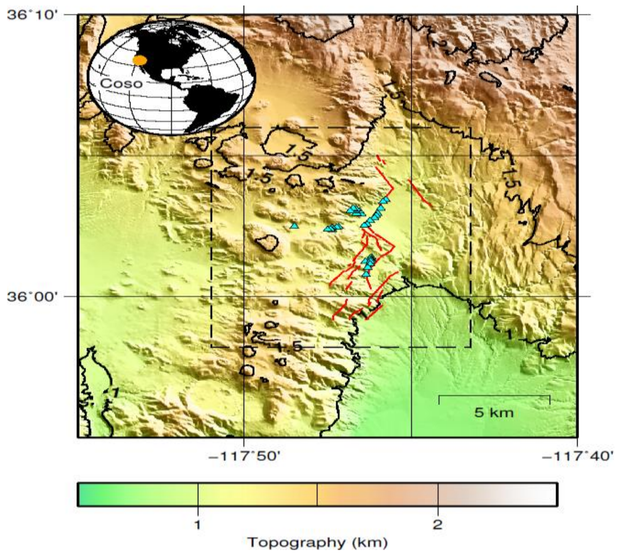
- Multi-steps for combined analysis
  - Individual analysis of geophysical datasets for 4 sites
    - Integrated interpretation
  - Iterative analysis using output of one method as input to another
    - MT <-> Seismic
  - Joint Imaging for common structure
- Analysis methods used
  - MT inversions for resistivity
  - Double-difference tomography (DDT) using micro-earthquake sources
  - Fully coupled elastic inversion

# Four Regions Being Studied

- Krysuvik & Hengill Reykjanes area, Iceland
  - Several producing geothermal fields
  - Collect new MEQ data, leverage with existing MEQ data from ISOR Network & MT data
- Krafla volcano, Iceland
  - Producing Geothermal field
  - First Iceland Deep Drilling Project (IDDP) well
  - Use existing MEQ and MT datasets
- Coso Hot Springs, USA
  - Producing geothermal field
  - Analyze existing MEQ and MT data

# Coso

| Original Planned Milestone/ Technical Accomplishment | Actual Milestone/Technical Accomplishment | Date Completed |
|---|---|---|
| Early in FY12 | Coso Joint Seismic-EM Model | May FY12 |
| Fall FY14 | Coso Full Tensor MT Analysis | Sept FY14 |




# Standard MT Inversion Workflow Problems and Issues

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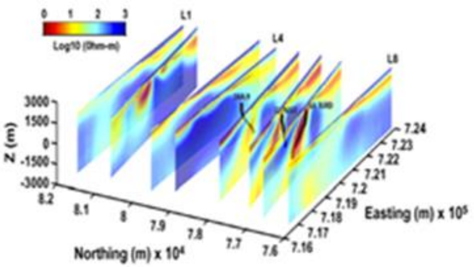
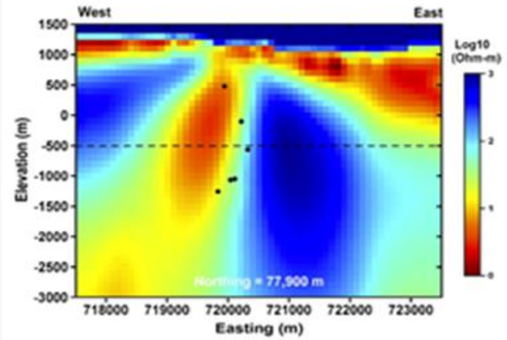
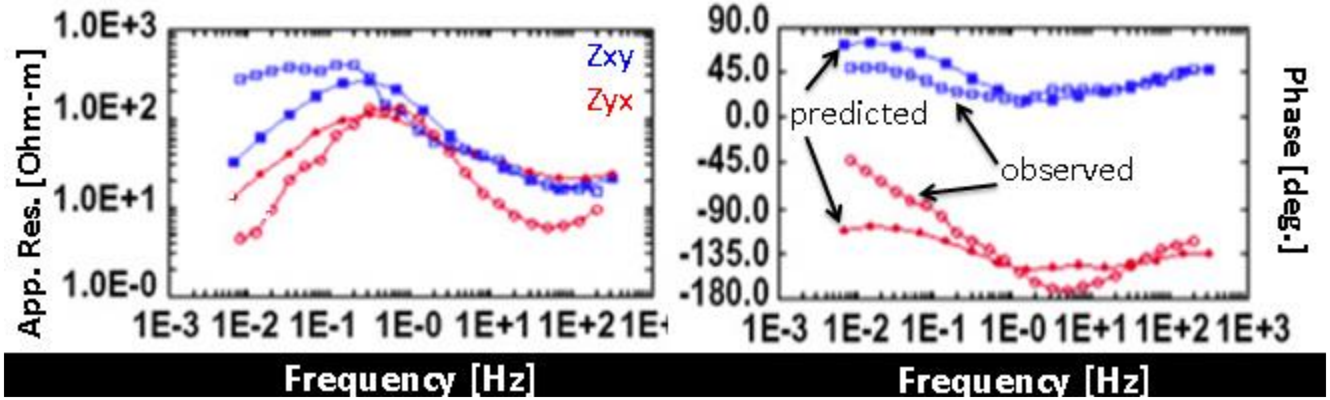
| | Starting Model | Data | Model |
|---|---|---|---|
| Newman et al., 2008 |  Interpolated 2-D model results | *Zxy, Zyx* *(5% error floors)* |  |



# Sequenced Workflow for 3-D full tensor inversion

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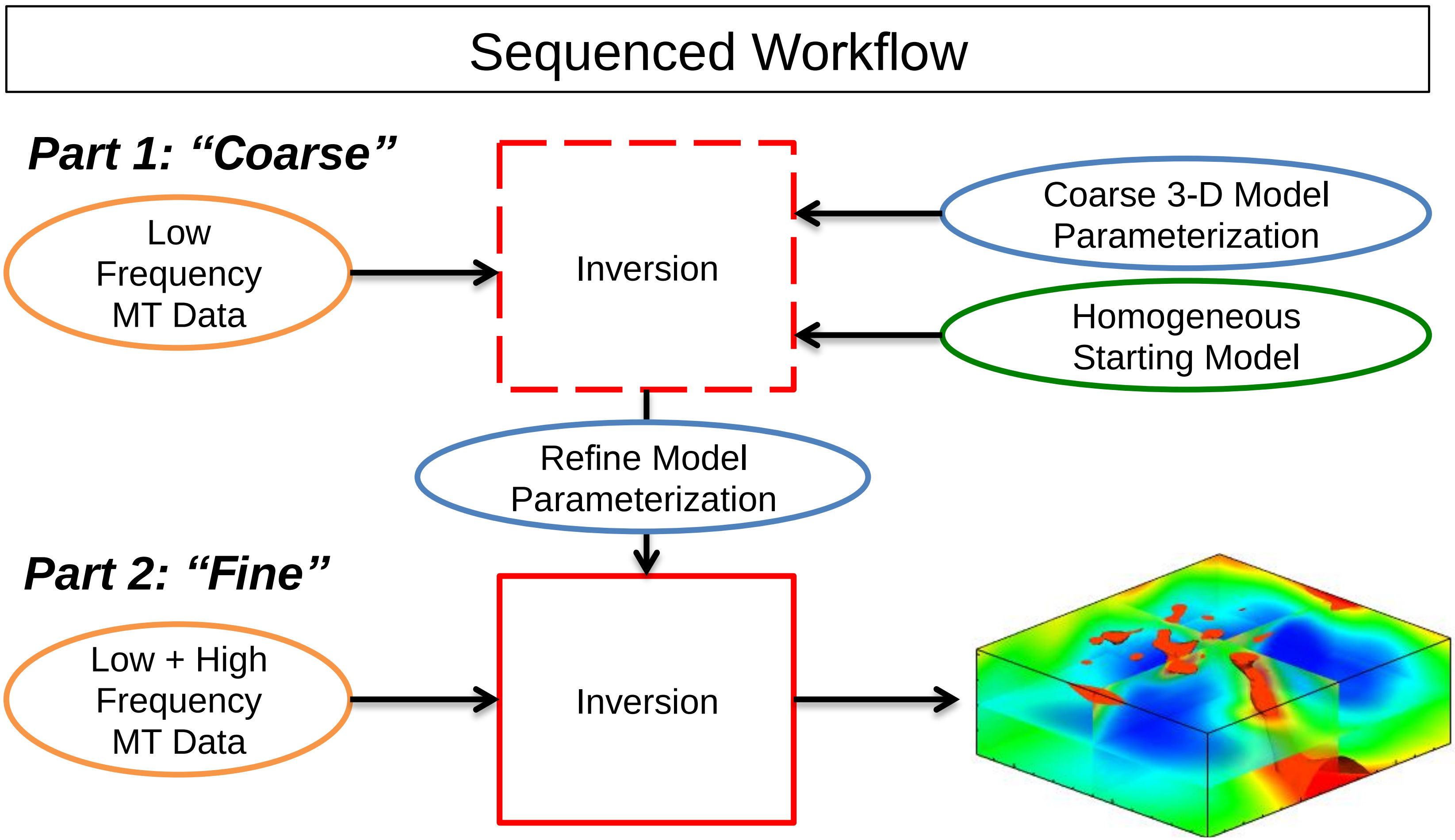
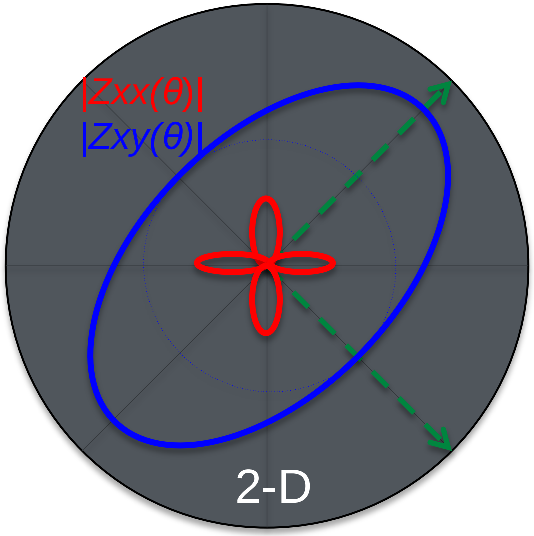



*Lindsey & Newman, 2014 (Geothermics)*

# 3-D Modeling of Full-tensor MT data

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix}$$



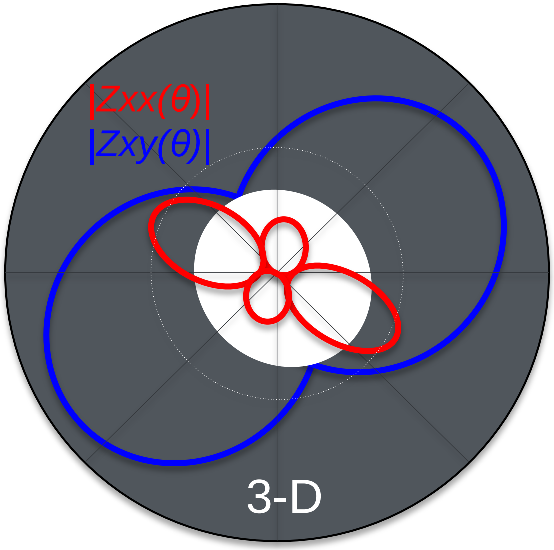





Image courtesy of NERSC

## EMGeo Inversion Algorithm

*Solve Maxwell's equations in 3-D using non-linear conjugate gradient method. Finite-difference methods used to predict data. Implemented in parallel, on Hopper Cray XT4 at the National Energy Research Scientific Computing Center (NERSC).*

$$\varphi = \sum_{n=1}^{2N} [(Z_n^{obs} - Z_n)/\varepsilon_n]^2 + \lambda \mathbf{m}^T \mathbf{W}^T \mathbf{W} \mathbf{m}$$

*Newman and Alumbaugh, 2000*

# 3-D Full-tensor MT Modeling

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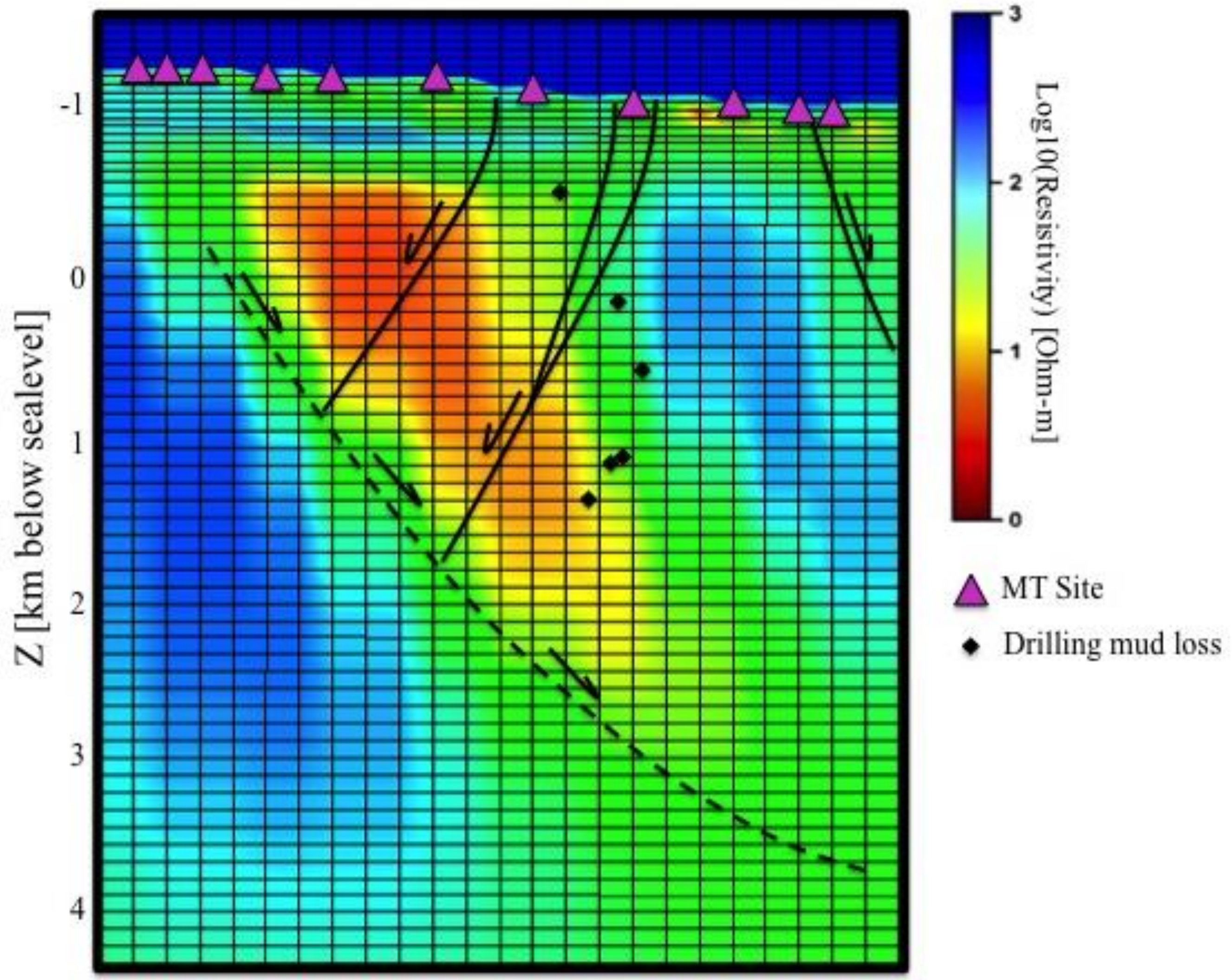
Inversion metadata
Sequenced workflow
10% error floors
~4000 processors
30 hours runtime
218 iterations
RMS=3.5

Seismic reflection interpretation overlayed from Unruh et al., 2008.

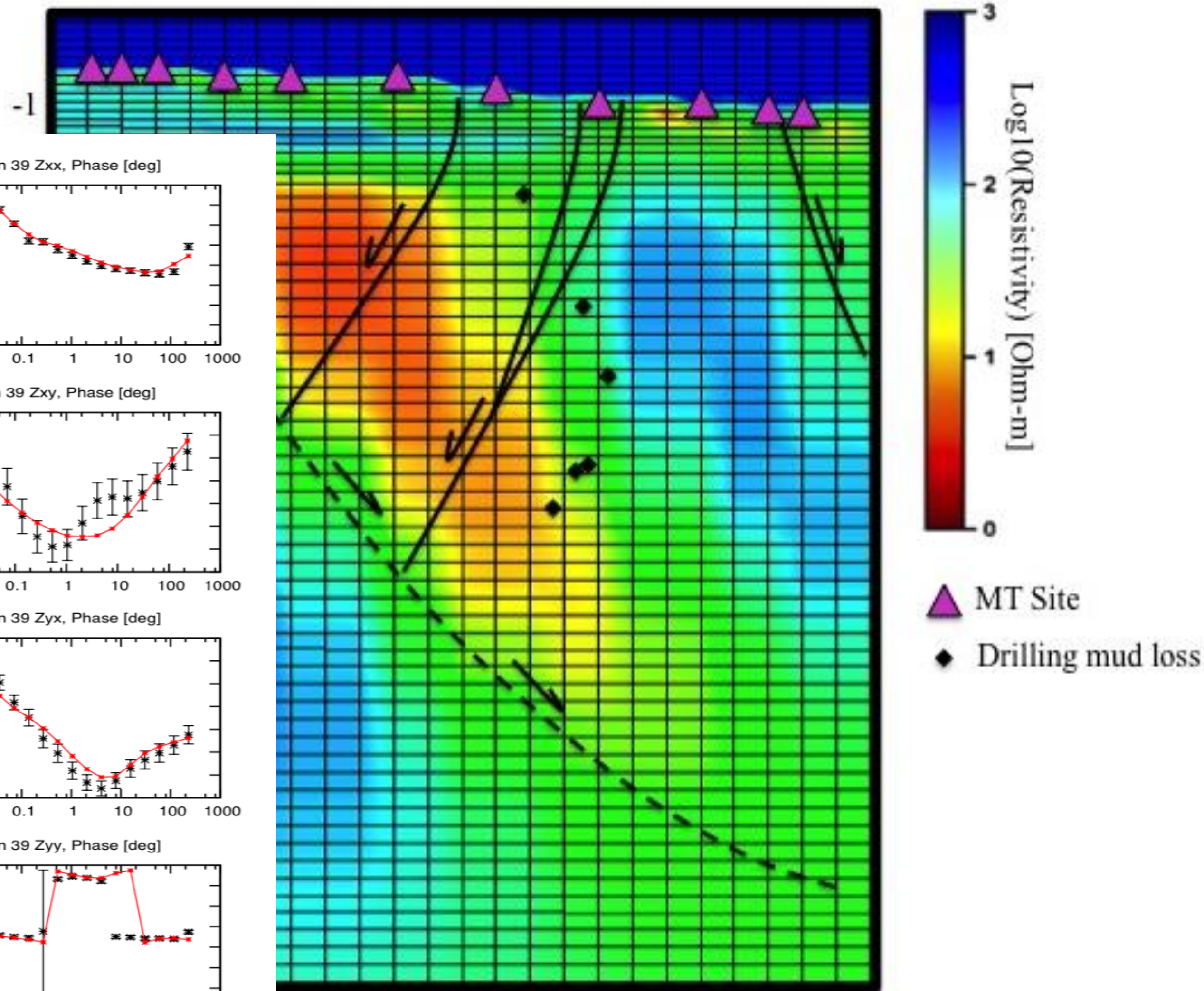
Mud loss locations overlayed from Newman et al., 2008.

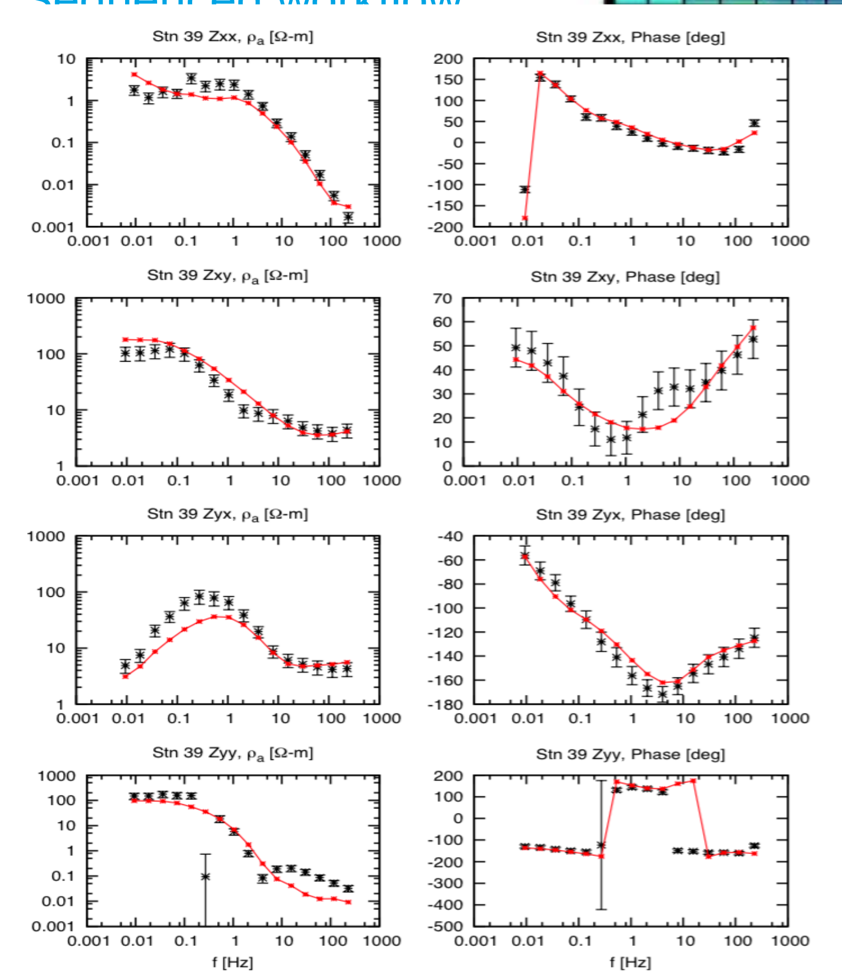


# 3-D Full-tensor MT Modeling

Inversion metadata

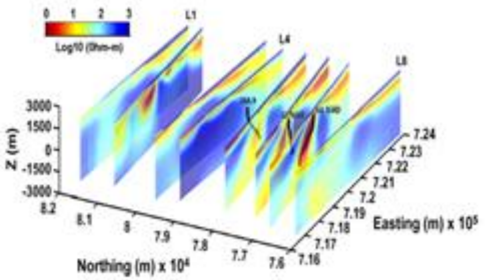
Sequenced workflow

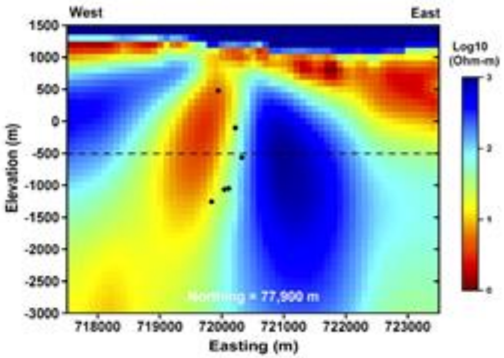


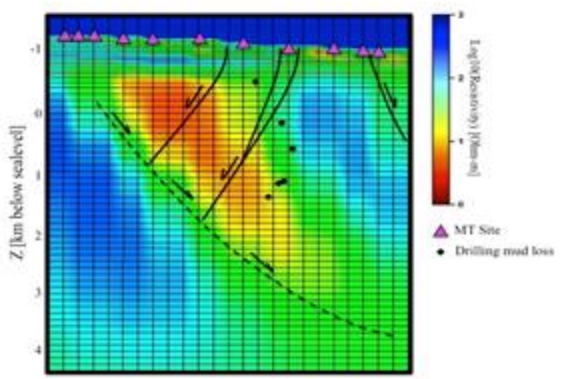



# 3-D Full Tensor MT Modeling



<table>
<tr><th></th><th>Starting Model</th><th>Data</th><th>Model</th></tr>
<tr><td>Newman et al., 2008</td><td>

Interpolated 2-D model results</td><td>Zxy, Zyx<br><br>(5% error floors)</td><td>
</td></tr>
<tr><td>Present Work</td><td>

*with sequenced workflow<br>(Lindsey & Newman, 2014)</td><td>Zxx, Zxy<br>Zyx, Zyy<br><br>(10% error floors with real errors above)</td><td>
</td></tr>
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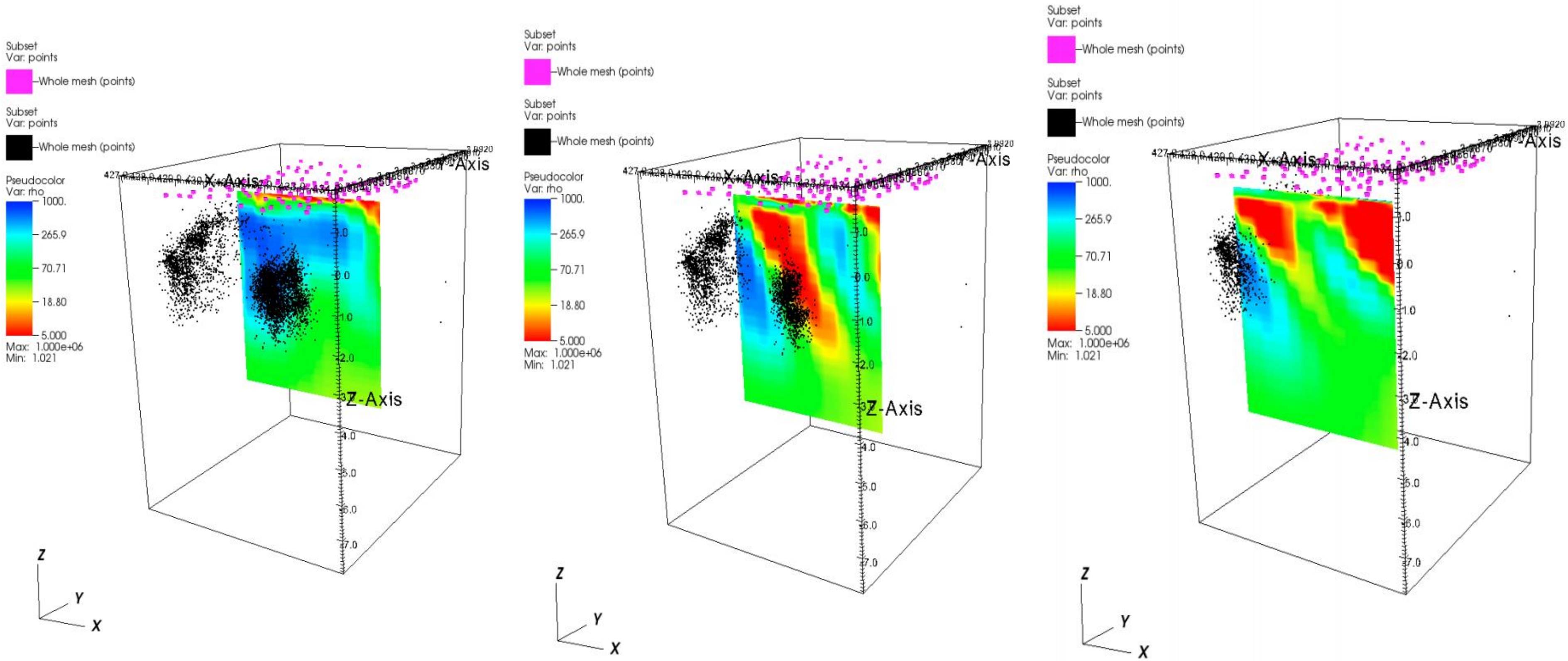
# 3-D Full Tensor MT Modeling
## much better correlations with seismicity



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# Krysuvik – Reykjanes

| Original Planned Milestone/ Technical Accomplishment | Actual Milestone/Technical Accomplishment | Date Completed |
|---|---|---|
| March FY12 | Krysuvik Resistivity Model | Spring FY12 |
| March FY13 | Continuously Operation MEQ Network – Reykjanes Area | Fall FY13 |
| March FY14 | Krysuvik Joint MEQ-MT Analysis | Fall FY14 |

# Joint MEQ-MT Analysis Krysuvik

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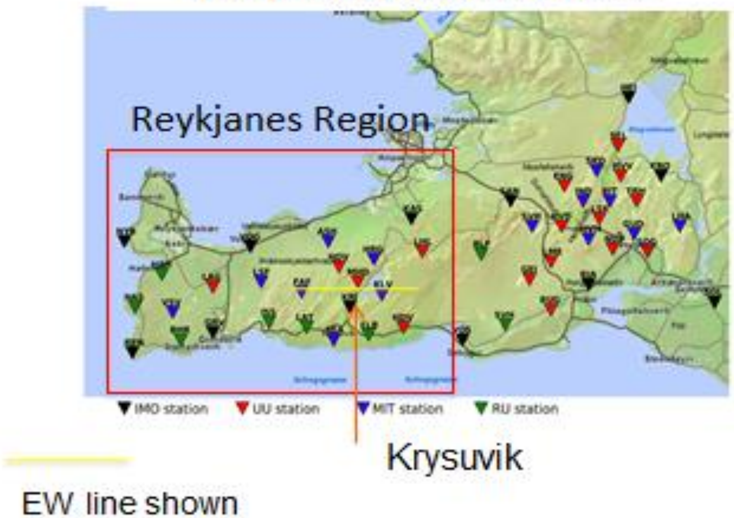
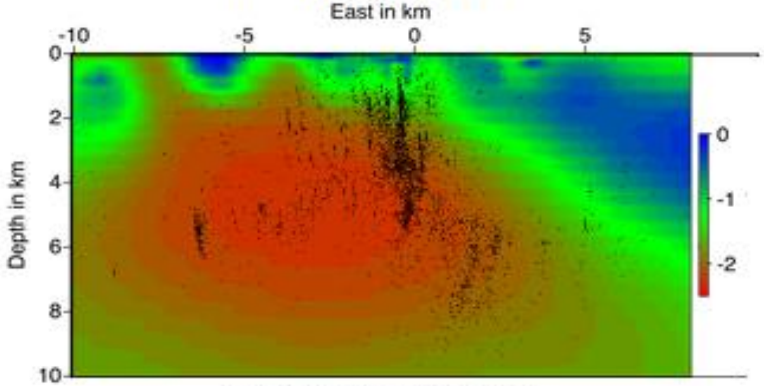
Hengill-Reykjnes Network

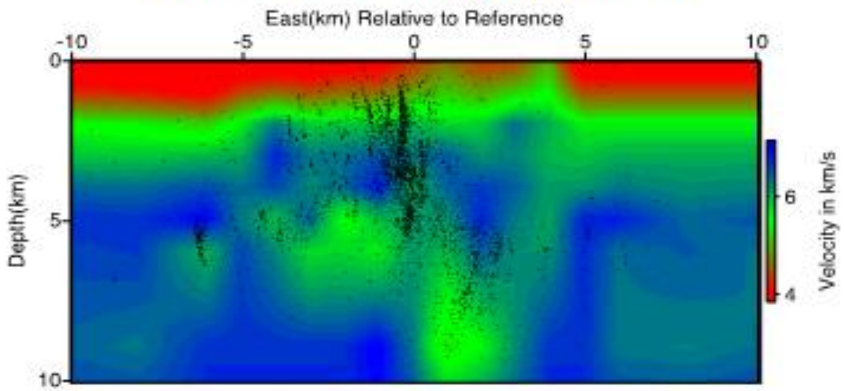



Vertical Cross Section Through LBL Resistivity Model




log resistivity from LBL

Double Difference Tomography Without Resistivity Constraint



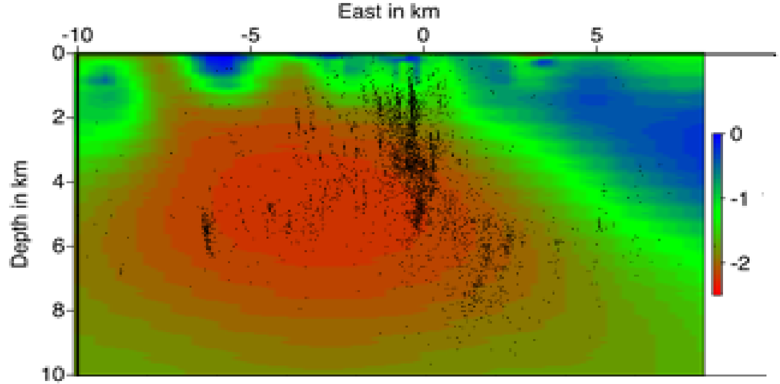

P-wave Velocity Through Reference

- Study Krysuvik Region
- Target for Geothermal Energy Development
- Network collaboration of Reykjavik University, Uppsala University and MIT
- Active seismic swarm
- Active uplift measured with GPS and InSAR

# Krysuvik – Joint Analysis

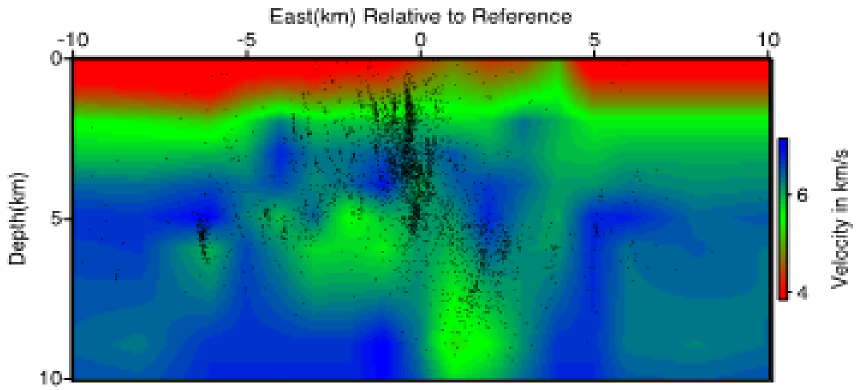


Vertical Cross Section Through LBL Resistivity Model




log resistivity from LBL

Double Difference Tomography Without Resistivity Constraint



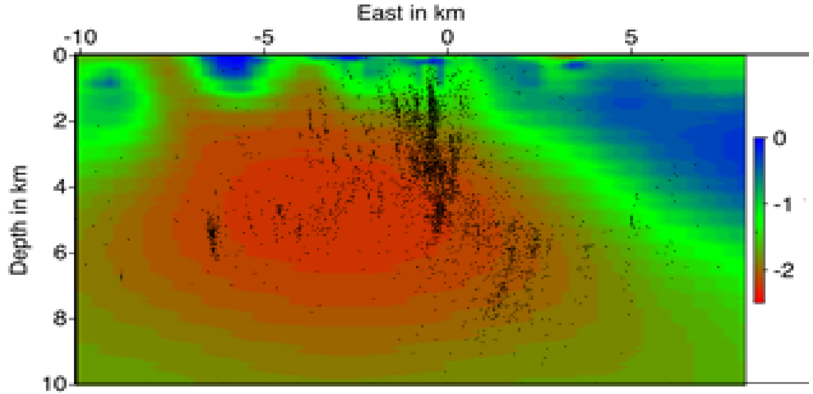

P-wave Velocity Through Reference

### Independent Inversions

- Weak correlation between models
- High Resistivity Zone and Low Velociy Zones centered a 5 km depth are similar
- Seismic inversion done with smaller grid spacing than would normally be done
  - Attempt to get grid scales between inversions more similar
  - This leads to features in seismic model that are poorly constrained
- Earthquakes seem to terminate at top of low velocity zone / high resistivity zone

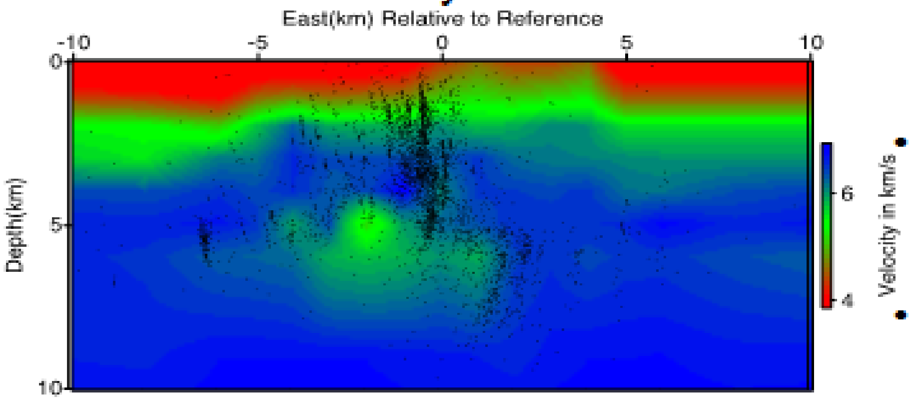
# Krysuvik – Joint Analysis

Vertical Cross Section Through LBL Resistivity Model




log resistivity from LBL

Double Difference Tomography With Resistivity Constraint




largemodel_ttw5_cg.3 P-wave Velocity Through Reference

## Seismic Model Constrained by Resistivity Model

- Good correlation between models
- Very little change in RMS misfit of seismic data (1 -2%)
  - Constrained seismic model is one of many models that fit data well
  - Resistivity constraint helps provide better seismic model
- High Resistivity Zone / Low Velocity Zones centered a 5 km depth are more similar
- Many poorly constrained portions of seismic model now lack structure
  - Desired outcome
- Earthquakes do terminate at top of low velocity zone / high resistivity zone

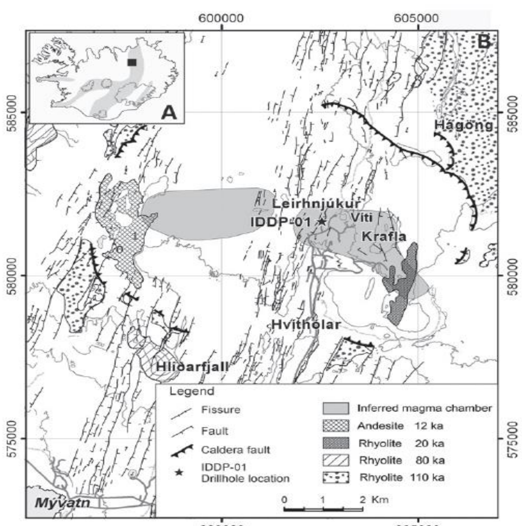
# Interpretation of Low Velocity/ High Resistivity Zone

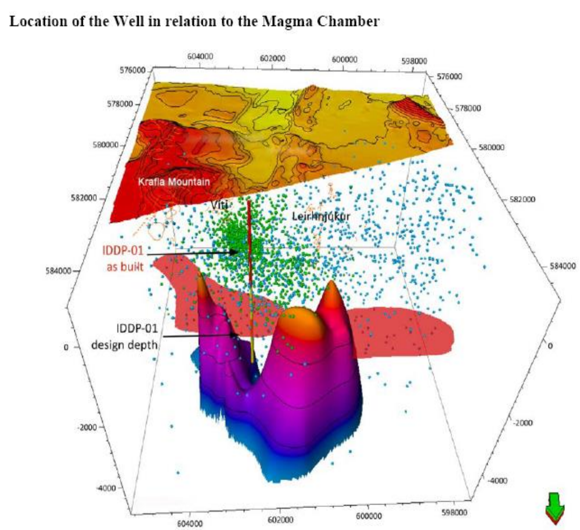
| Partial melting | Supercritical fluid | Ductile Material |
|---|---|---|
| Low Vp, Vs | Low Vp, Vs | Low Vp, Vs |
| High Vp/Vs ratio | Low Vp/Vs ratio | ? |
| Low resistivity | High resistivity | High Resistivity |
| Seismicity Terminates | No Seismicity Termination | Seismicity Terminates |

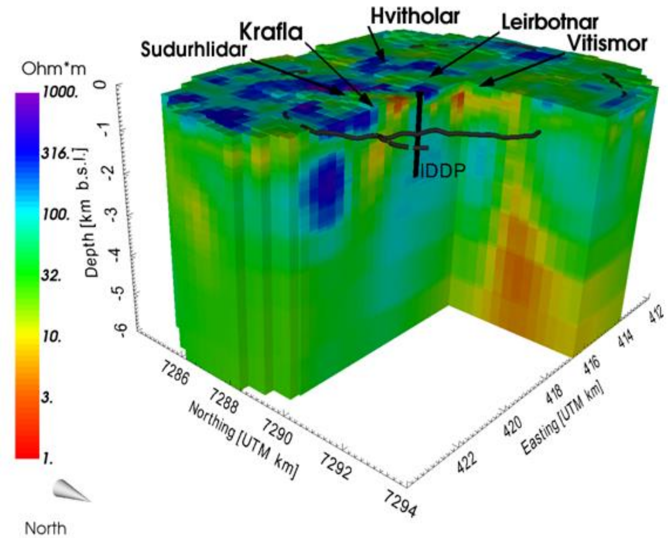
Items in black are features in model that are consistent with the interpretation
Items in red are required features that are not in the model

# Krafla

| Original Planned Milestone/ Technical Accomplishment | Actual Milestone/Technical Accomplishment | Date Completed |
|---|---|---|
| Mid FY13 | Krafla Model Appraisal (3D resistivity cube) | October FY13 |
| End of FY13 | Krafla Joint MEQ-MT Analysis (Final results) | December FY13 |



# Krafla Resisitivty Cube Appraisal
# Three Codes - Three Images



## Geothermal zones

The structures of the zones coincide

Resistive cores

Super Critical Fluids – at IDDP-well

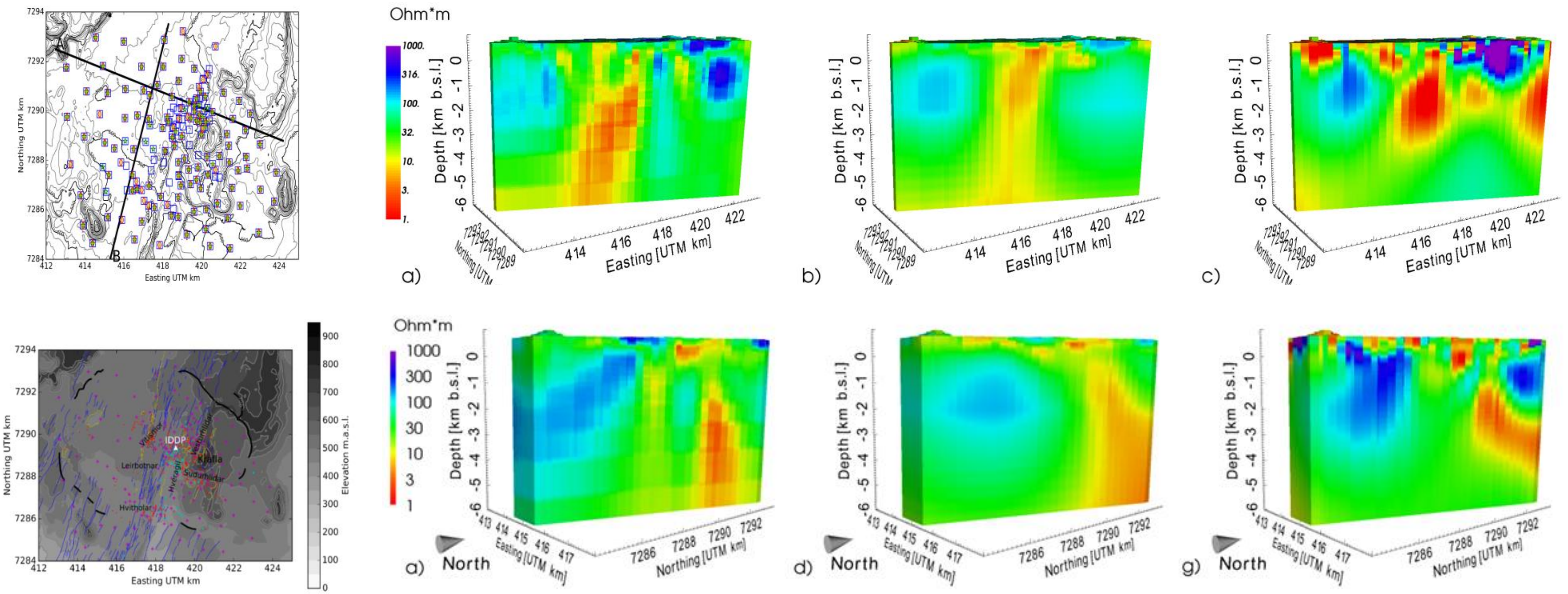
Deep conductive body NW of IDDP-well

Interpreted as plausable magmatic zone

## Dissimilarities

Near surface-dependent initial model

Model edges and data coverage




**ISOR - WSINV3DMT** **LBL - EMGeo** **UBC – MT3Dinv**

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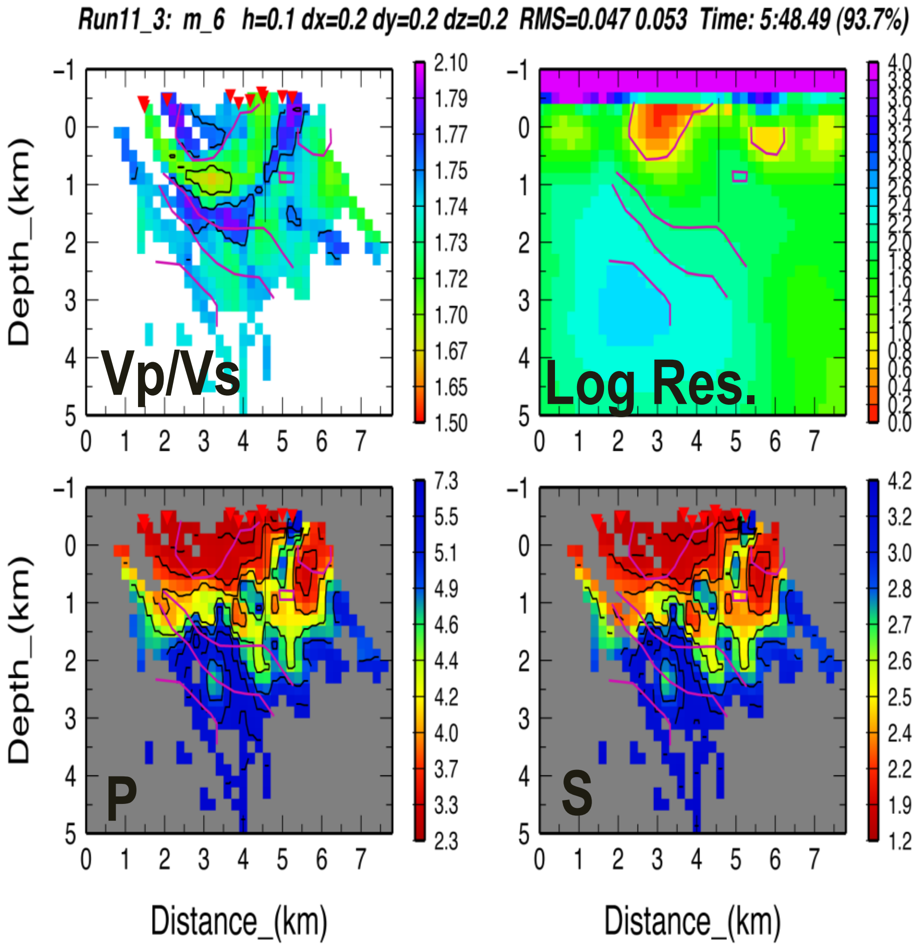
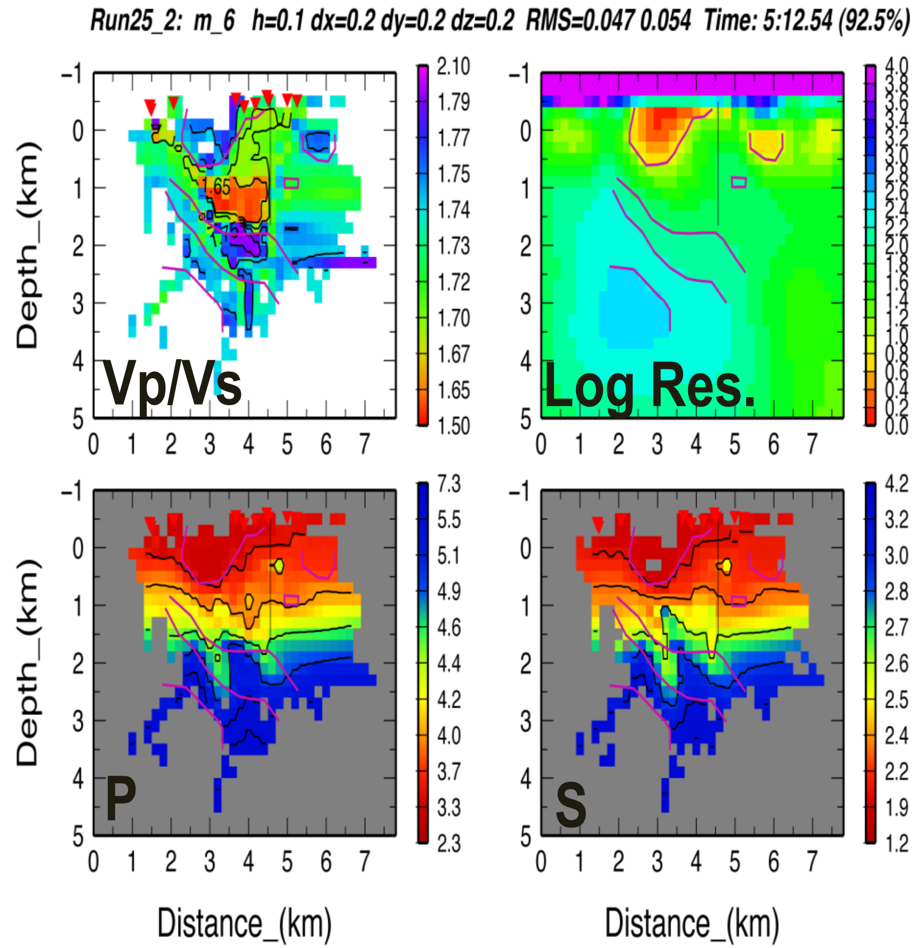
## Not Coupled to Resistivity Structure



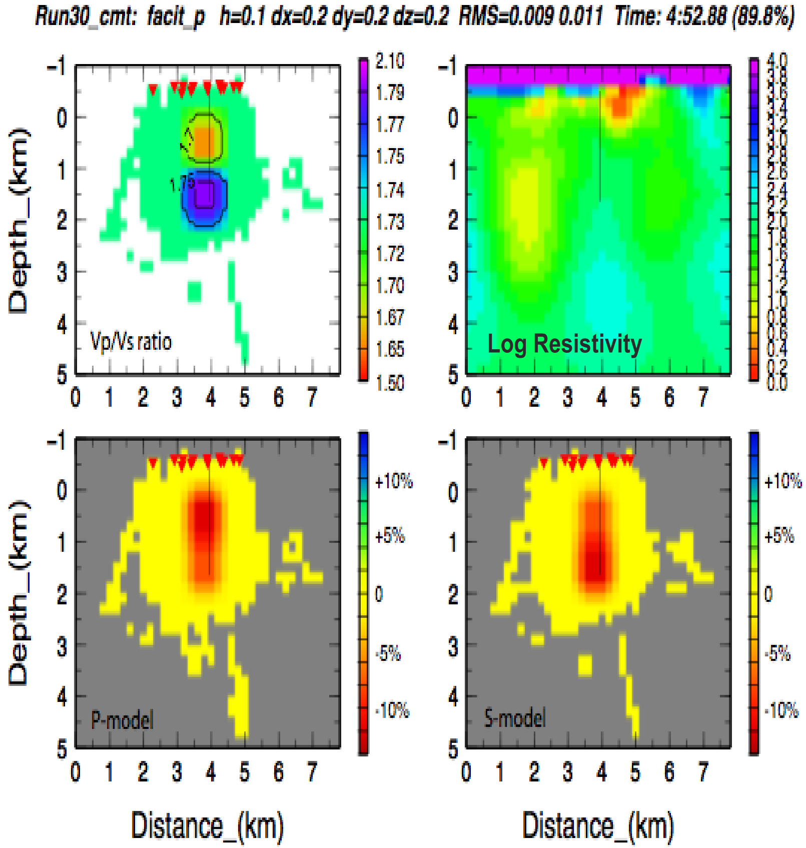

## Coupled to Resistivity Structure



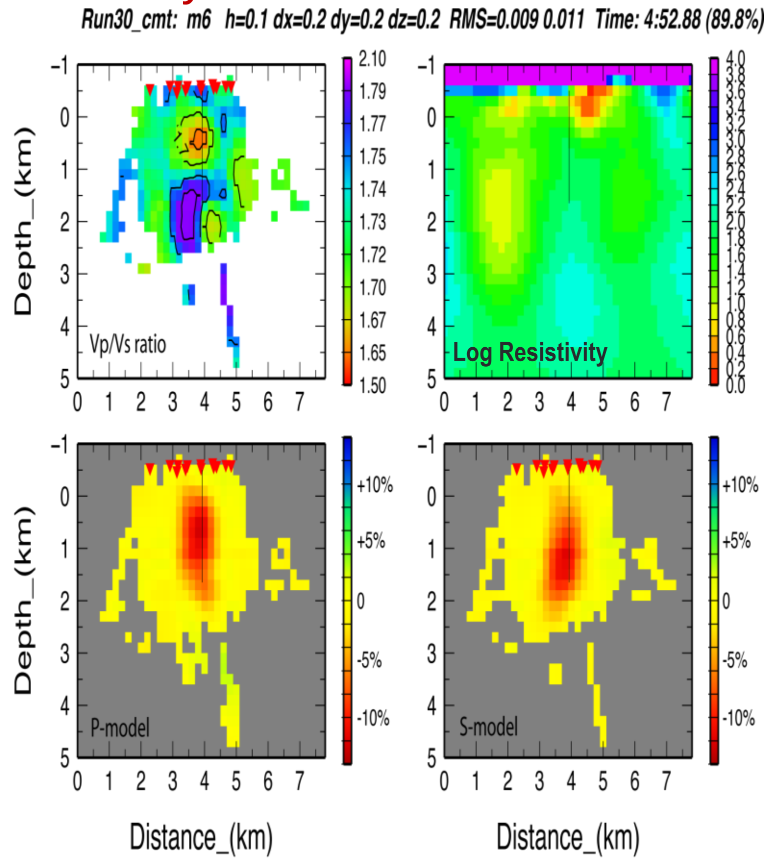
# Joint MT-MEQ Analysis – Krafla Model Appraisal



## Proposed Model




## Synthetic Reconstruction

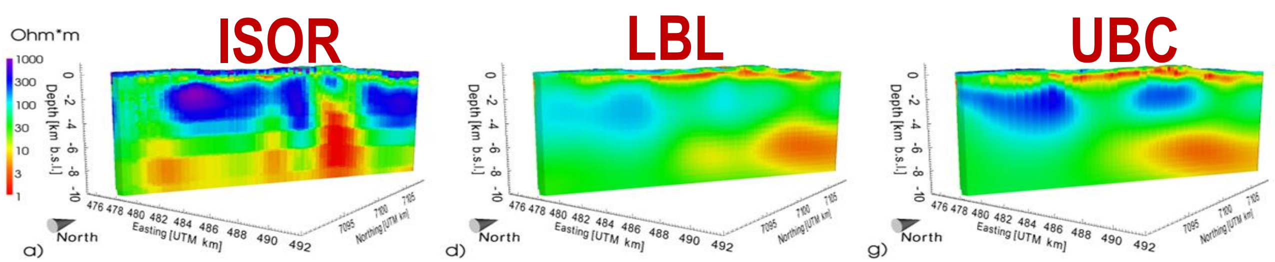


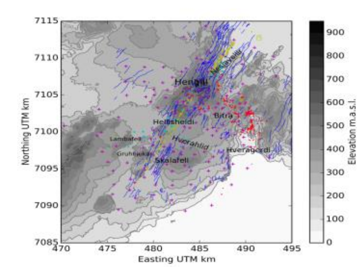

## Assessment

- The seismic model is over-parameterised
- Models not dramatically different with/without coupling to the MT-model
- The cross-gradient smooth's the seismic velocity model … but the model fits the data equally well
- Velocity models poorly resolved below 2 km depth

# Hengill – Reykjanes

| Original Planned Milestone/ Technical Accomplishment | Actual Milestone/Technical Accomplishment | Date Completed |
|---|---|---|
| March FY13 | Hengill 3D Resistivity Model Appraisal: three imaging codes | Spring FY14 |
| March FY13 | Continuously Operation MEQ Network – Reykjanes Area | Fall FY13 |
| March FY14 | MEQ Velocity Analysis | In progress (U. Uppsala) |
| Sept FY14 | Joint MEQ-MT Analysis | Pending |



# Future Directions

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- Funding for project formally ended in FY14
- MEQ analysis still  proceeding with Hengill (U. Uppsala)
- Joint MT-MEQ analysis for Hengill - pending
- Resistivity cube appraisal
  - Consider application to Coso and Krysuvik with independent modeling codes
- Full tensor MT analysis & workflow
  - Consider application to Krafla, Krysuvik & Hengill data sets

# Summary

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- Correctly-formulated joint inversion has the capability to combine differing datasets to maximize the information obtained about geothermal targets
  - Useful for geothermal exploration, site characterization, and reservoir assessment
- Clear improvements in use of MT for geothermal
  - Full Tensor Analysis & Improved Inversion Workflows
  - Model Appraisal using Independent Modeling Algorithms
- Collected new data in Iceland and analyzed existing/new data from 4 geothermal areas using MT, Seismic, and Joint analysis methods
  - Individual and joint analysis provides new insight into structure of geothermal fields

# Project Management

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Timeline:

| Planned Start Date | Planned End Date | Actual Start Date | Current End Date |
|---|---|---|---|
| 5/15/2010 | 9/30/2014 | 5/15/2010 | 9/30/2014 |

Budget:

DOE Share: $3,205,226
Funding received in FY09: $0
Funding for FY10: $750,226
Funding for FY11: $175,000*
Funding for FY12: $830,000
Funding for FY13: $725,000
Funding for FY14: $725,000

*ISOR and RU funding from GEORG Program (GEOthermal Research Group) & Swedish Science Foundation*

| Federal Share | Cost Share | Planned Expenses to Date | Actual Expenses to Date | Value of Work Completed to Date | Funding needed to Complete Work |
|---|---|---|---|---|---|
| 2/3 | 1/3 | $3,205,226 (DOE) | $3,205,226 (DOE) | $4,807,839 (DOE+Cost Share) | $0 (DOE) |