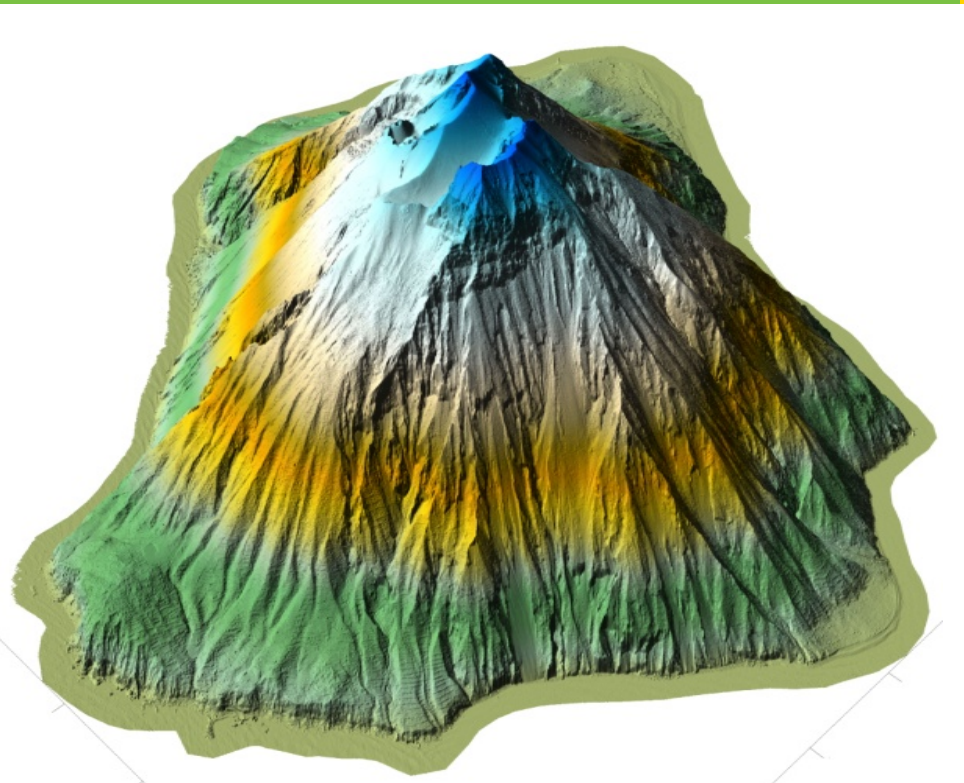
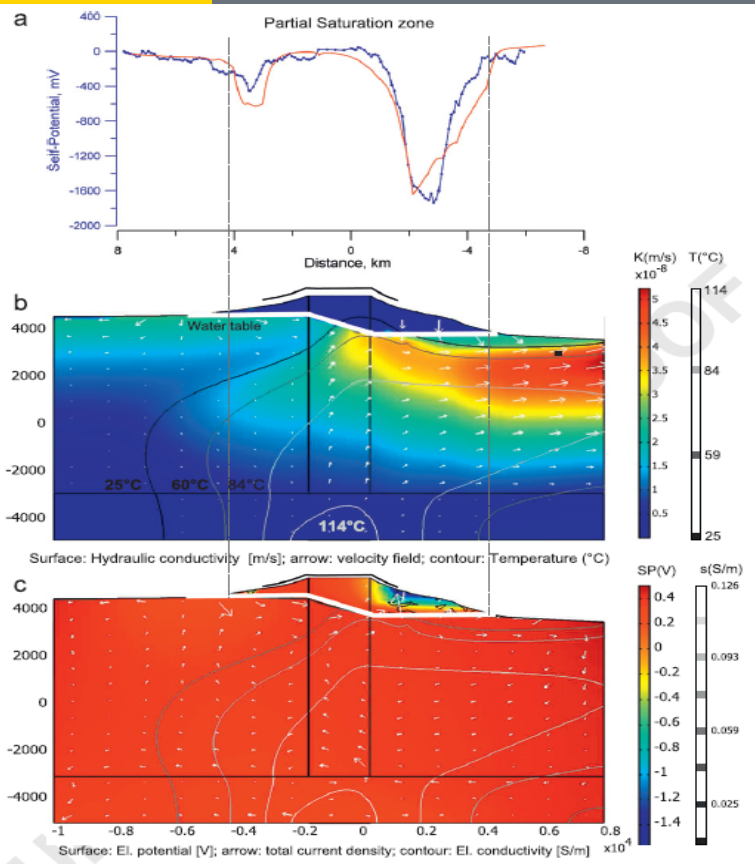
Component Technologies R&D:

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





Time-lapse Joint Inversion of Geophysical Data and its Applications to Geothermal Prospecting - GEODE

Project Officer: Mark Ziegenbein

Total Project Funding: $635,000

Principal Investigators:
Andre Revil and Mike Batzle (Colorado School of Mines)
Ezra Zemach (ORMAT)

Relevance/Impact of Research

Objectives of the project

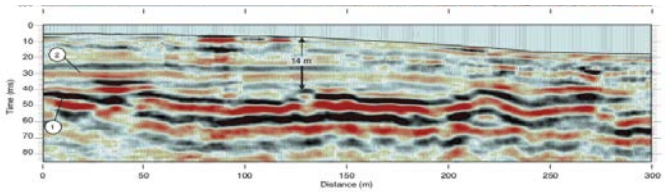
- Forward modeling geophysical response with fluid flow/heat modeling
- Joint inversion (stochastic/deterministic) for ground water flow imaging
- Combined passive and active geophysical methods /new methods
- Technical feasibility at Jersey Valley geothermal field (Nevada)

Impact on costs

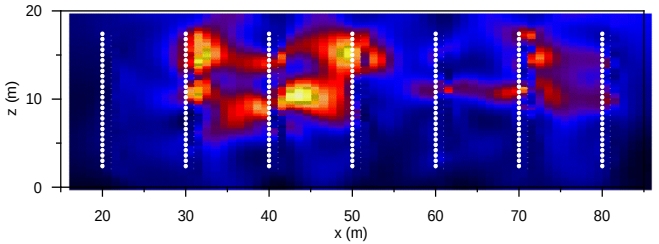
- Decrease of the costs of drilling through better characterization targets
- Better management of existing fields through time lapse geophysics
- Methodologies can be easily transferred to other DOE test sites
- ORMAT can use the new approaches for both production and site management

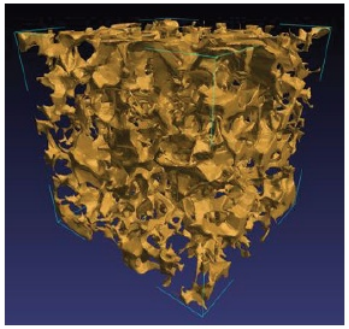
Scientific/Technical Approach

Geophysics



(1) Joint inversion
(2) Time-lapse
(3) Seismic+EM



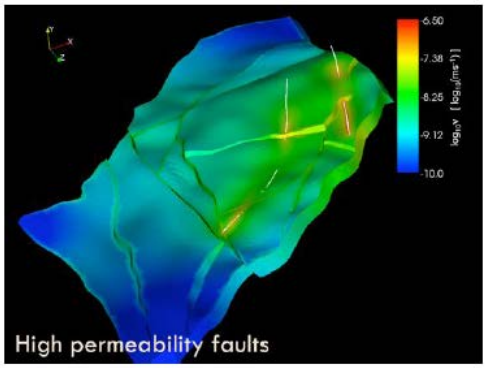


Petrophysics

(1) Seismic properties
(2) Resistivity (*m* and *n*)
(3) Effet of saturation

Geology and texture

(1) Sedimentology
(2) Tectonics (faults)



Reservoir Modeling

(1) Multiphase flow
(2) Multiscale porous media

Accomplishments, Results and Progress

PHASE 1 Assemble Data & Model Development

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Task 1 Assemble & Assess Data	Milestone 1 Previous data compiled	01/01/2013
Task 2 Joint Inversion Model (CSM)	Milestone 2: Meetings (ORMAT/CSM)	01/01/2013
	Milestone 3 Codes released	01/01/2013
Task 3 : Database (ORMAT and CSM)	Milestone 4: Measurements complete	01/01/2013
Task 4 Petrophysics	Milestone 5: Petrophysics	In progress
Task 5 Testing EM system	Milestone 6: Acquisition plans	In progress
Task 6 Acquisition Planning		01/01/2013

Decision Point: Go - No go" Decision of field acquisition (January 2013)

Publications: 8 publications in the peer-reviewed literature

Publications (Phase 1 of the project)

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

Karaoulis M., A. Revil, A., J. Zhang, and D.D. Werkema, Time-lapse cross-gradient joint inversion of cross-well DC resistivity and seismic data: A numerical investigation, Geophysics, 77(4), D141–D157, 2012.

Karaoulis M., A. Revil, D.D., Werkema, P. Tsourlos, , and B.J. Minsley, IP4DI SOFTWARE: A 2D/3D time lapse tomographic algorithm for DC resistivity, induced polarization, and frequency-domain induced polarization data, Computers and Geosciences, 2012.

Revil A., A. Jardani, J. Hoopes, M. Karaoulis, C. Colwell, **M. Batzle**, A. Lamb, and K. van Wijk, Non-intrusive estimate of the flow rate of thermal water along tectonic faults in geothermal fields using the self-potential method, FastTIMES, 16(4), 2011.

Karaoulis M., **A. Revil**, Minsley B., M. Todesco, J. Zhang, and D.D.Werkema, 4D Time-lapse gravity inversion, submitted to Geophysical Journal International.

MacLennan, K., **M. Karaoulis**, and **A. Revil**, Complex conductivity tomography using low-frequency cross-well electromagnetic data, submitted to Geophysics, 2012.

Byrdina S., D. Ramos, J. Vandemeulebrouck, P. Masias, **A. Revil**, A. Finizola, K. Gonzales Zuniga, V. Cruz, Y. Antayhua, and O. Macedo, Influence of the regional topography on the remote emplacement of hydrothermal systems with examples of Tiscani and Ubinas volcanoes, Southern Peru, Earth and Planetary Research, 2013.

Soueid Ahmed, A., A. Jardani, **A. Revil**, and J.P. Dupont, SP2DINV: A 2D forward and inverse code for self-potential problems, submitted to Computers & Geosciences, 2012.

Zhou J., **A. Revil**, **M. Karaoulis**, D. Hale, and J. Doetsch, Image-guided Inversion of Electrical Resistivity Data, submitted to Geophysical Journal International.

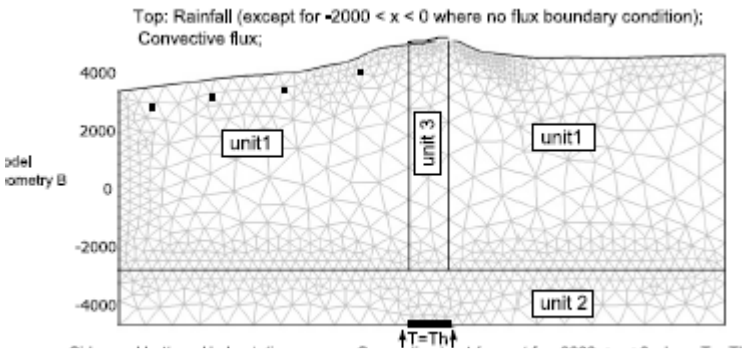
Prediction geophysical data through forward modeling (Task 1)

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

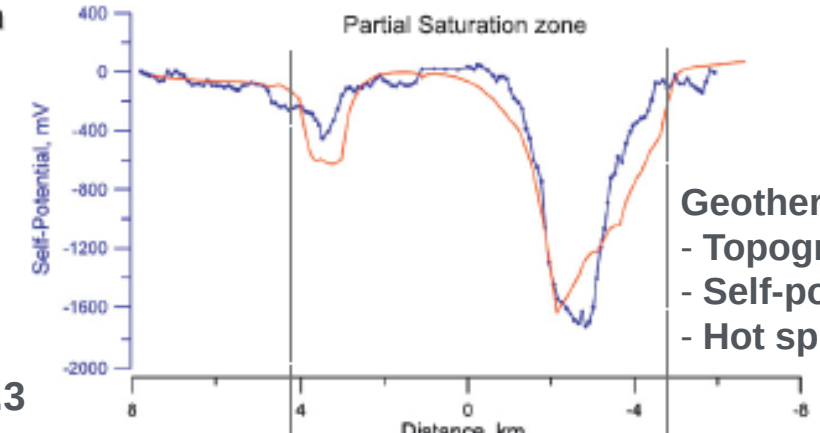
Influence of the regional topography on the remote emplacement of hydrothermal systems with examples of Ticsani and Ubinas volcanoes, Southern Peru

Earth and Planetary Science Letters
365 (2013) 152–164

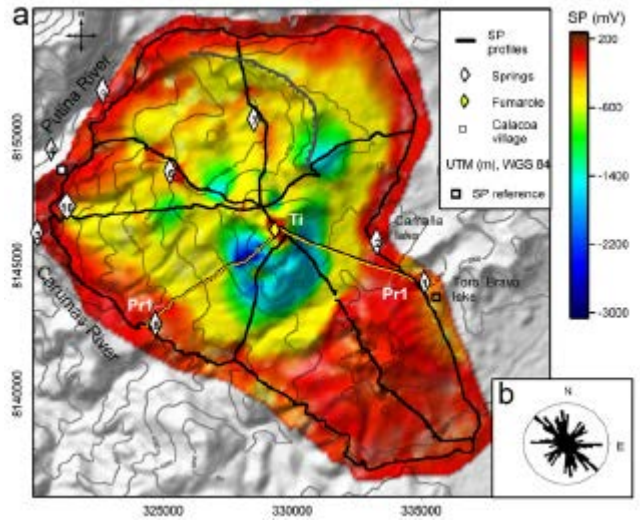
S. Byrdina [a,*], D. Ramos [b], J. Vandemeulebrouck [a], P. Masias [b], A. Revil [a,c], A. Finizola [d], K. Gonzales Zuñiga [e,1], V. Cruz [b], Y. Antayhua [b], O. Macedo [e]



Numerical tool: Comsol Multiphysics 4.3



Geothermal field:
- **Topography controls**
- **Self-potential data**
- **Hot springs data**



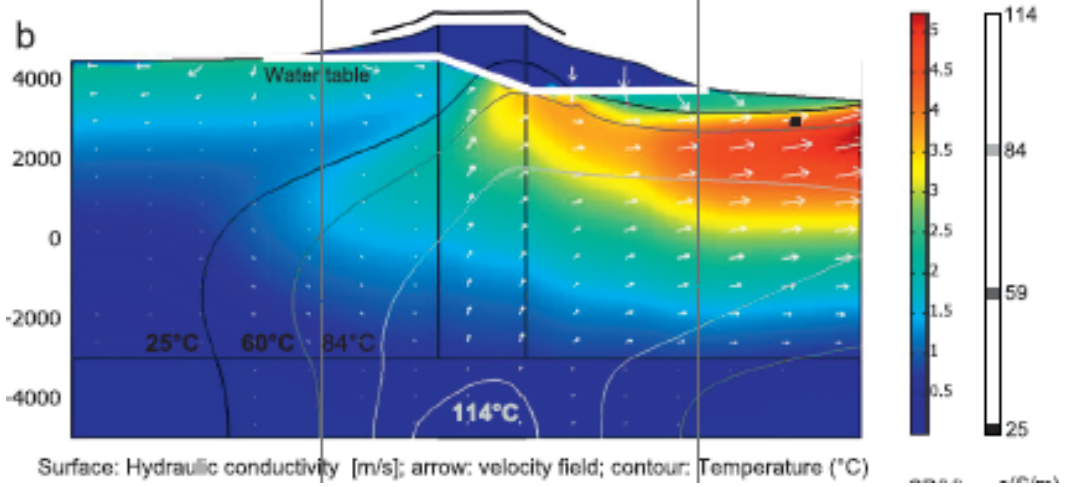


Image guided inversion (Task 2)

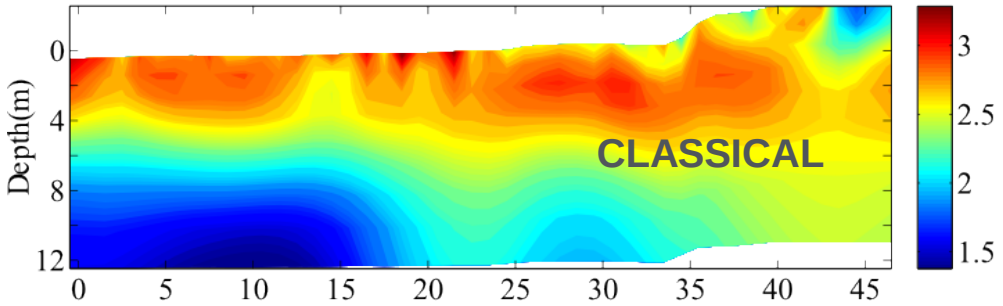
Image-guided Inversion of Electrical Resistivity Data

J. Zhou , A. Revil ,M. Karaoulis D. Hale and J. Doetsch

(submitted to Geophysical Journal international)

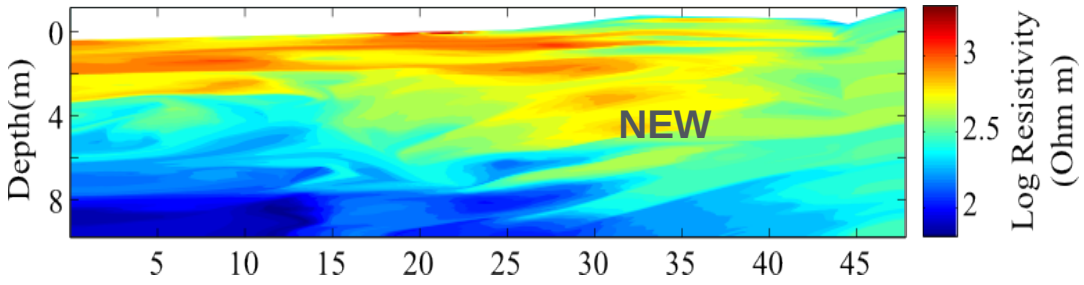
Goal: Increase resolution resistivity inversion

a) Gauss-Newton inversion with smoothing

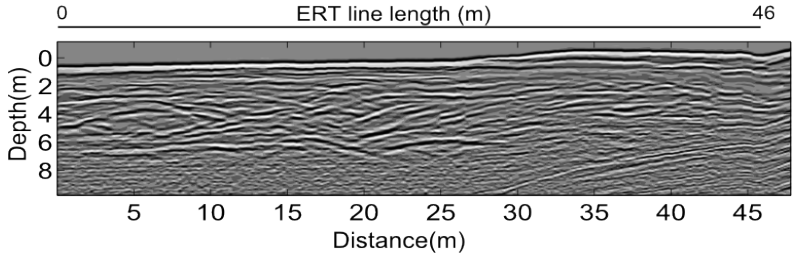


Manipulation model covariance matrix

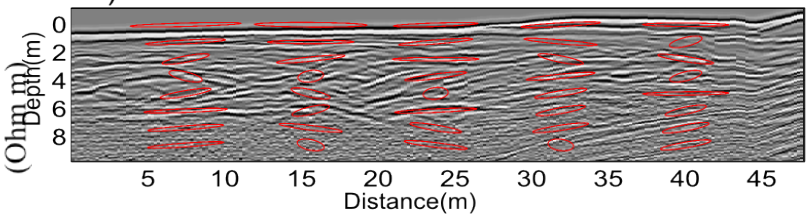
b) Image guided inversion with interpolation



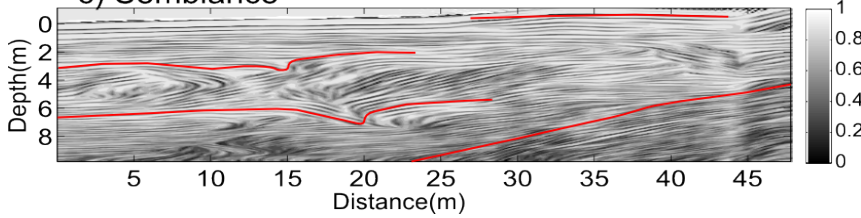
a) Guiding Image (GPR)



b) Metric Tensor Field



c) Semblance

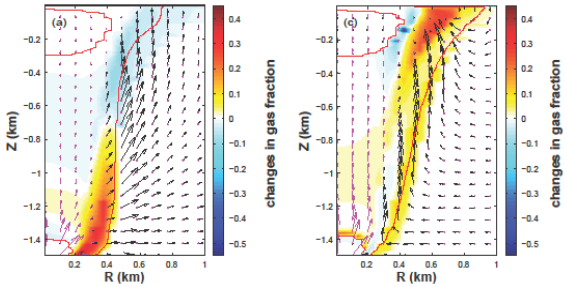


Next step: inversion MT+seismic data

(test Upper Arkansas Valley Colorado)

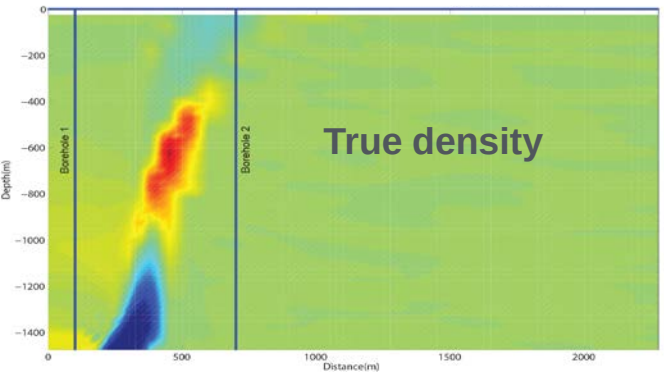
Time lapse gravity inversion

Karaoulis M., **A. Revil**, Minsley B., M. Todesco, J. Zhang, and D.D.Werkema, 4D Time-lapse gravity inversion, submitted to Geophysical Journal International.



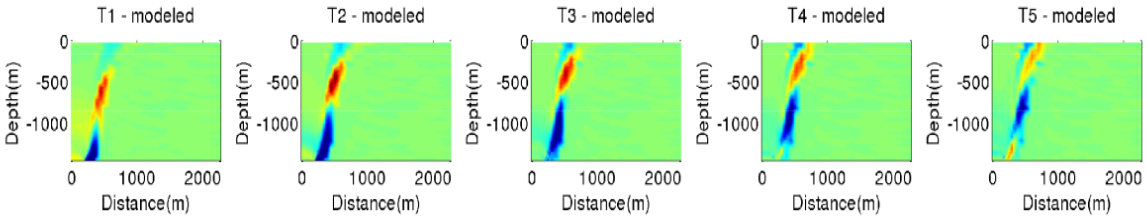
1) Forward modeling (TOUGH)

2) Forward modeling gravity field



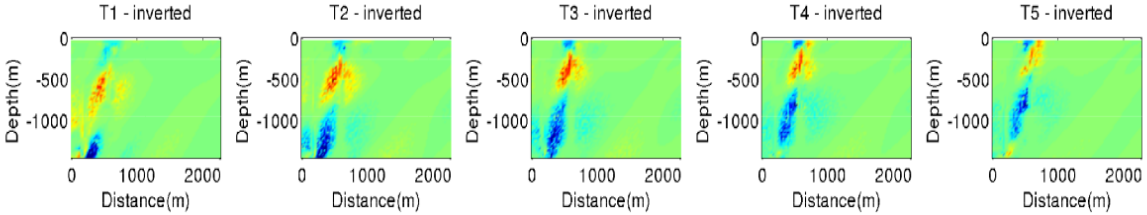
2D+time inversion

3) Time-lapse inversion of the gravity data



True density distribution

(use of an active time constraint)



Inverted density distribution

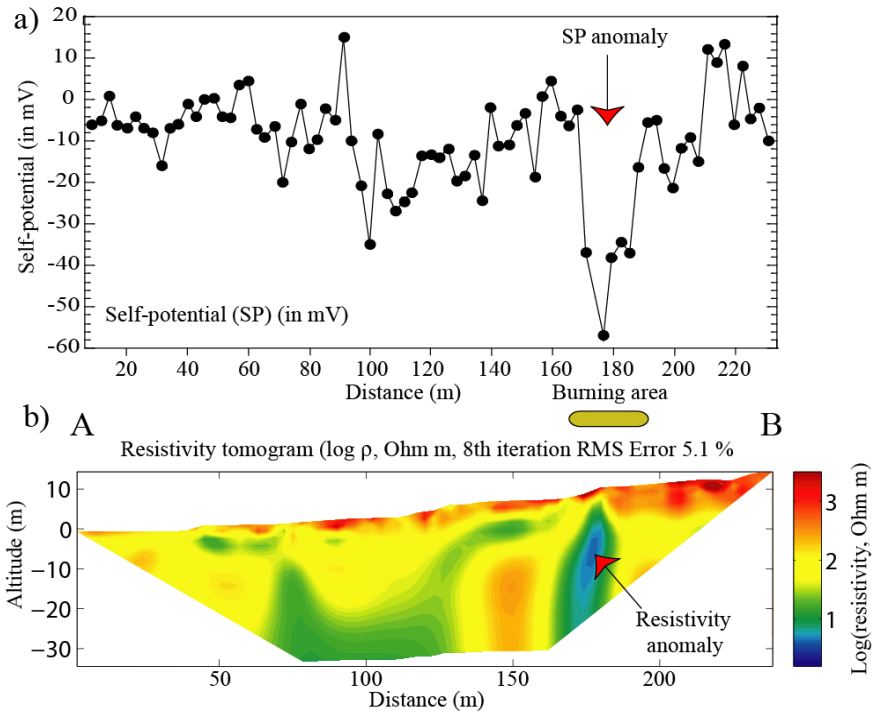
Next step: fully coupled inversion

Example of test of the joint inversion Localization of coal burning front (Task 2)

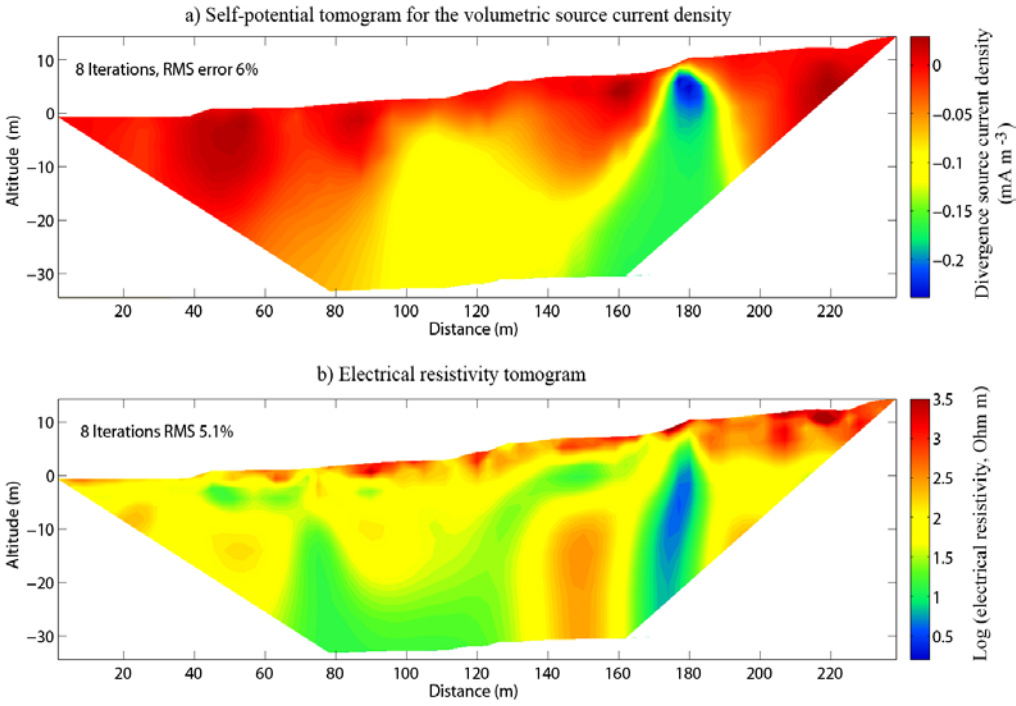
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

A. Revil, **Karaoulis M.**, et al, In press in Geophysics

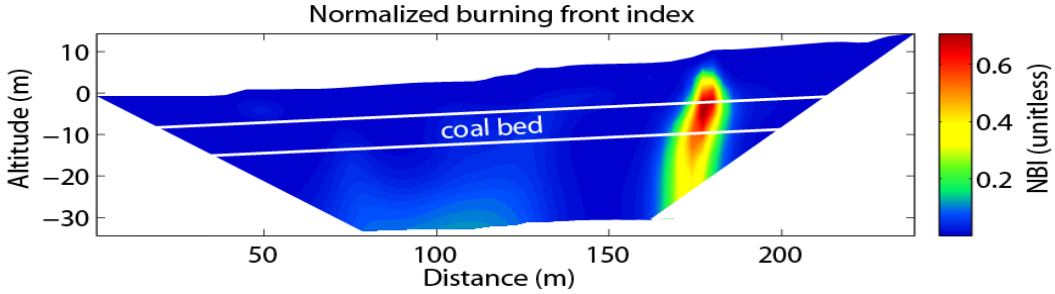
1) Self-potential and resistivity data



2) Joint inversion of the geophysical datasets



3) Determination of the target (burning front)

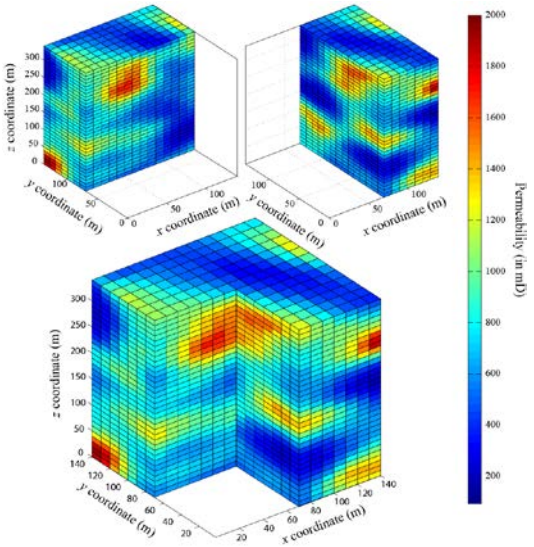


Next step: application to a geothermal target

Coupled Inversion (Task 2)

Wang, J., A. Revil, M. **Karaoulis** et al, in preparation for Geophysics

Multiphase flow in heterogeneous reservoir



Flow information transferred to the Inverse problem in geophysics

a) True Resistivity Model

16 days 32 days 48 days 64 days 80 days

TRUE

b) Resistivity Model Inverted by RES3DINV with each data misfit smaller than 0.01

16 days 32 days 48 days 64 days 80 days

CLASSICAL INVERSION

c) Inverted Resistivity Model using two–phase flow with total data misfit smaller than 0.16

16 days 32 days 48 days 64 days 80 days

NEW INVERSION

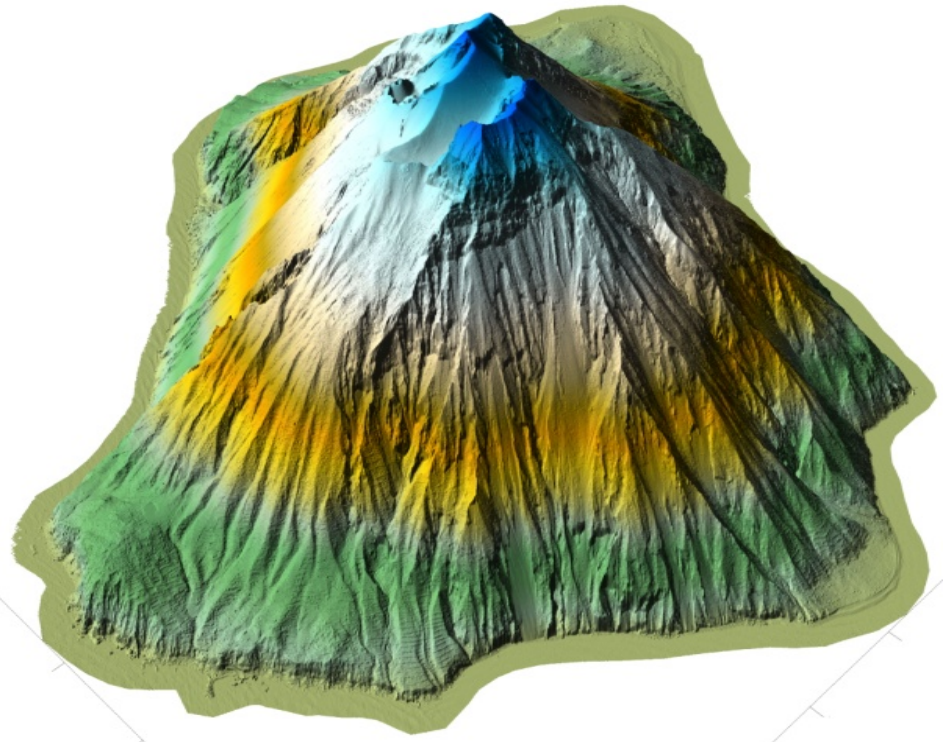
4 5 6 7 8 9 10 11
Resistivity (Ohm m)

Application to Stromboli (Task 1)

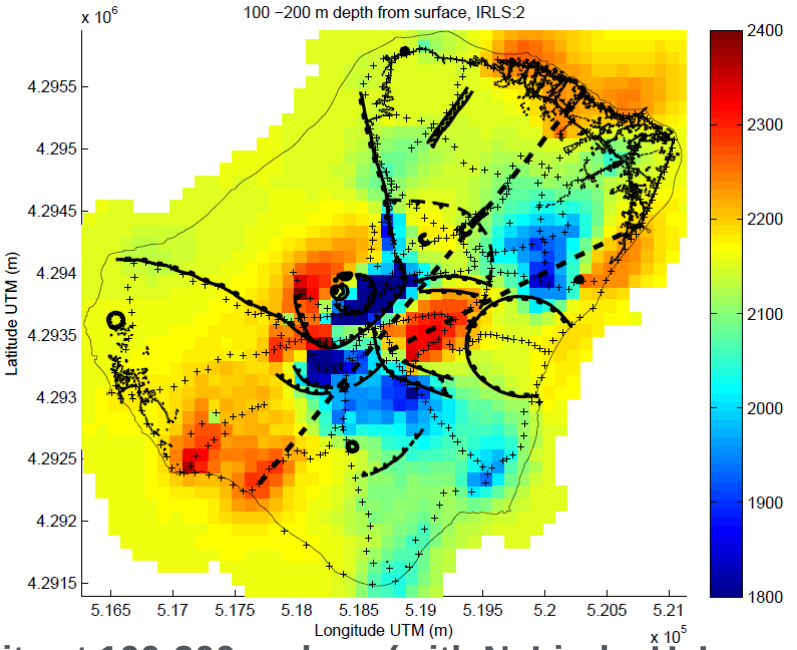
Joint inversion of the resistivity/gravity

1) 3D resistivity tomography done

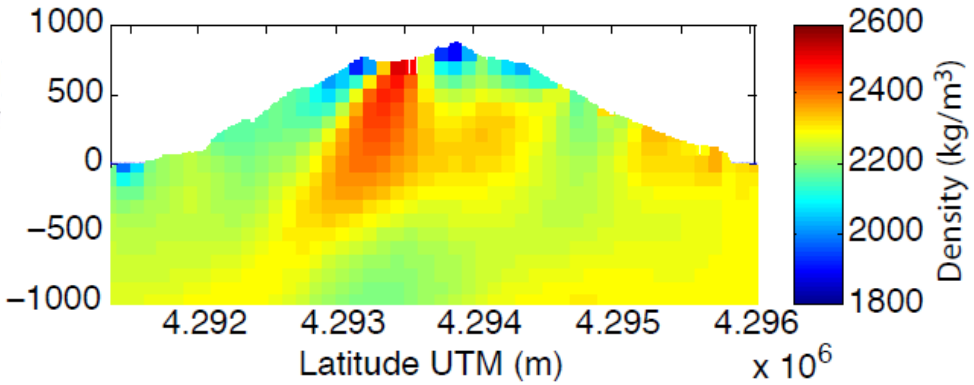
2) 3D gravity inversion done



High resolution DEM of Stromboli



Density at 100-200 m deep (with N. Linde, U. Lausanne)



Preparation of a paper for Nature Geosciences

Database GIS (Tasks 3)

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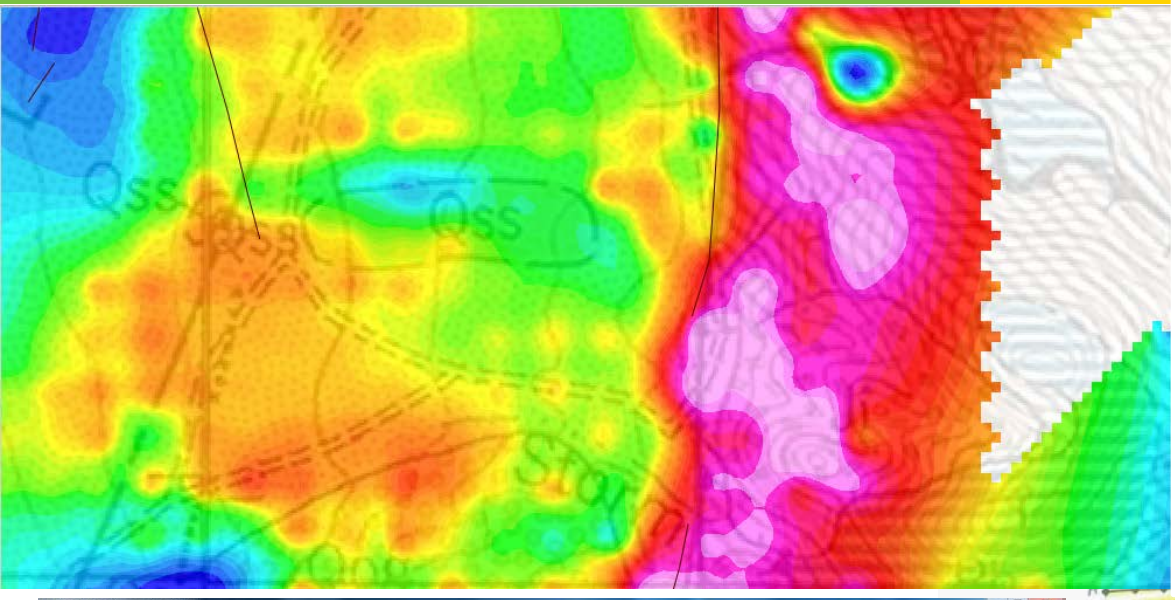
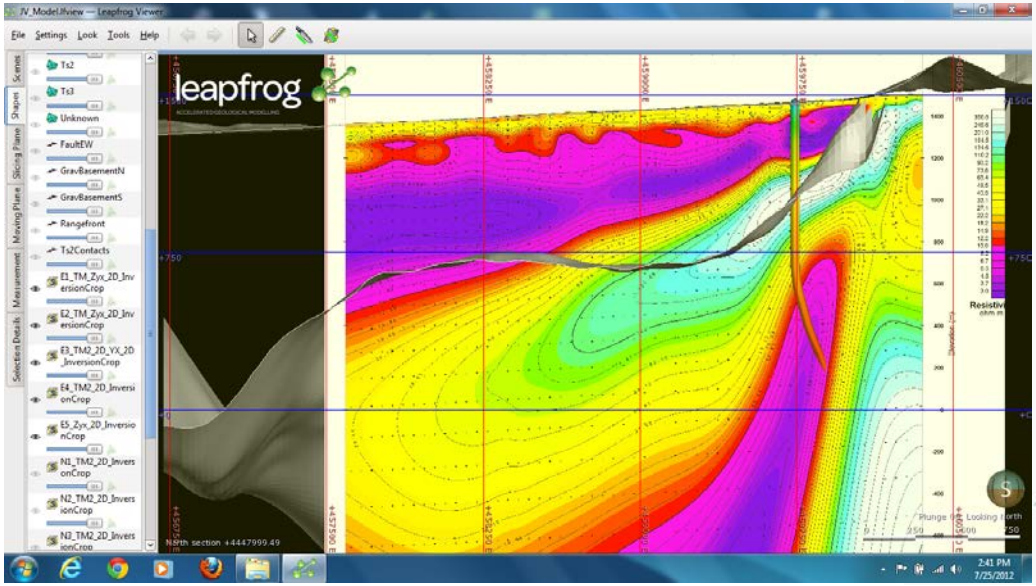
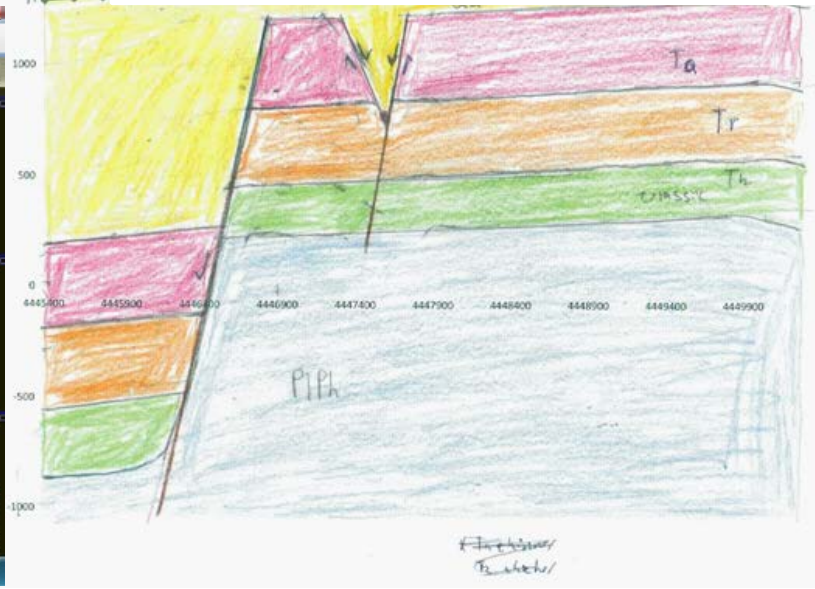


1) Resistivity survey (IP) Gavity, Mag
2) Radon-thoron soil
3) Water chemistry
4) Geological mapping
5) Gravity survey
6) 3 slim-holes data
7) 9 full-sized wells
8) Well-testing (flow/injection)
9) Conceptual reservoir modeling
10) Tracers test
11) Leapfrog 3D structural model
12) GIS database





Application to Jersey Valley (Tasks 4 and 5)

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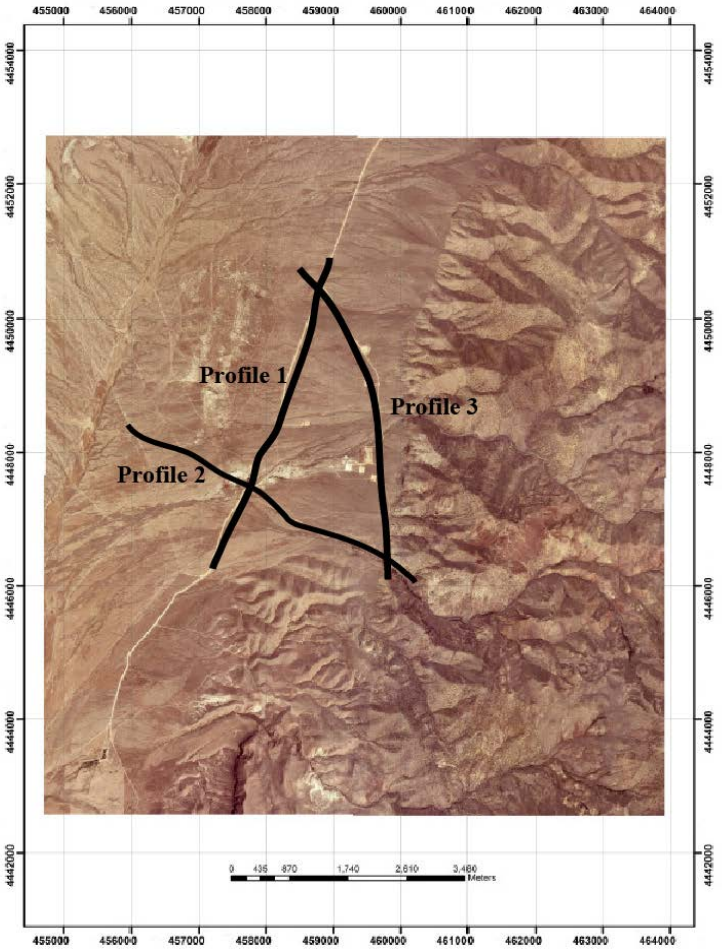
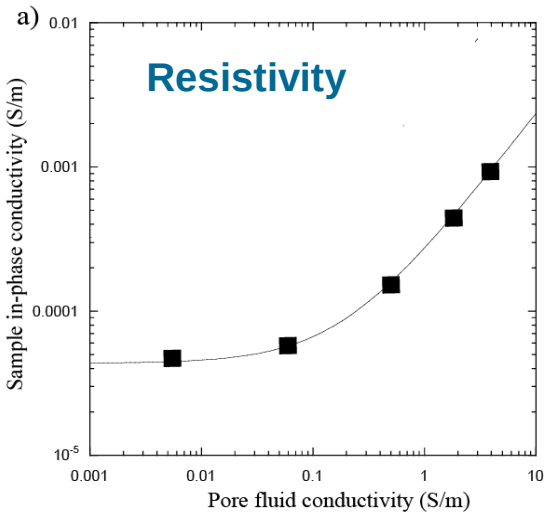
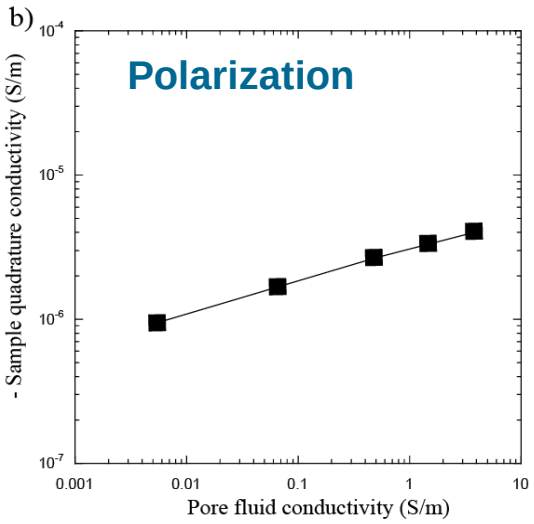


Profiles perform in March 2013





Petrophysics and core measurements

Future Directions (year 2)

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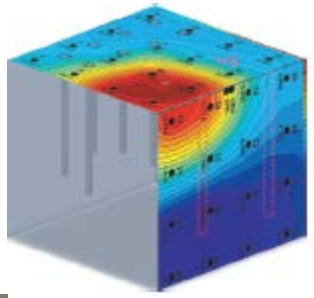
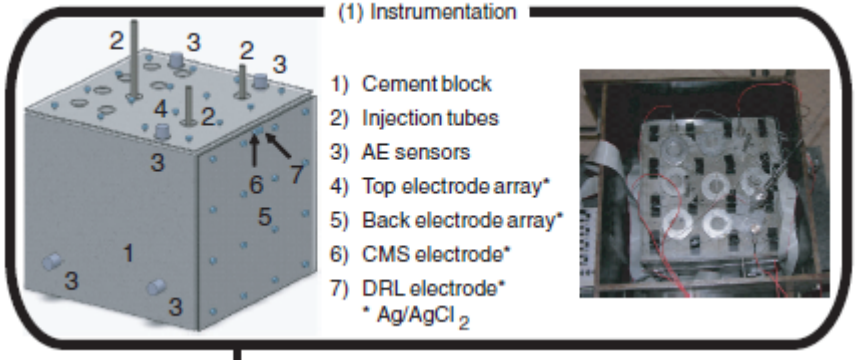
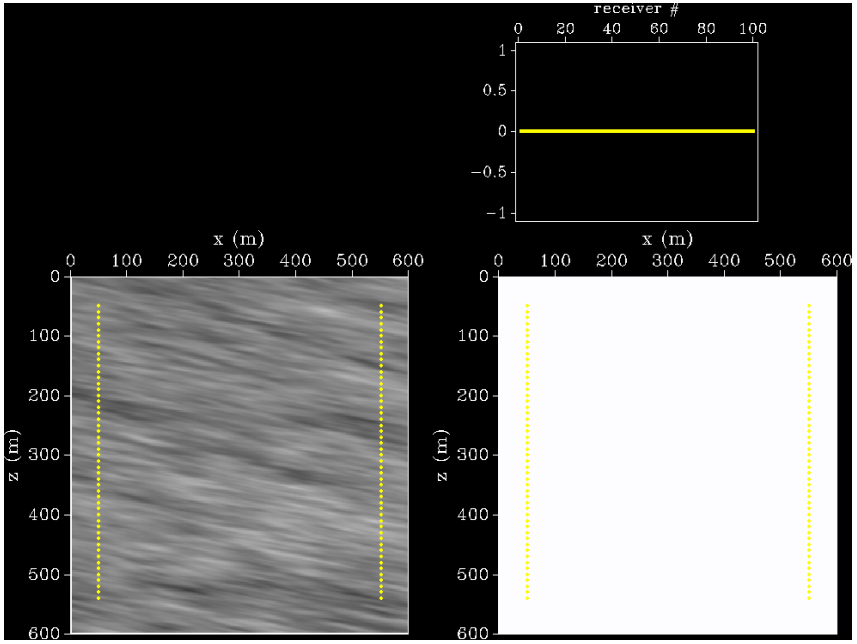
Milestone or Go/No-Go	Status & Expected Completion Date
Task 6 permitting	9/1/2012 Done
Milestone 7 –Permits obtained	1/1/2012 Done
Phase II Application to Jersey Valley Commercialization	
Task 1 Build Jersey Valley numerical model	
Milestone 8 Initial joint inversion model	10/01/2013 In progress
Task 2 Collect geophysical data	03/01/2013 In progress
Milestone 9 Data reduction/inversion	06/01/2013 In progress
Task 3 Joint inversion data Jersey Valley	06/01/2013 Not done
Task 4 Interpret results with geologic info	08/01/2013 Not done
Task 5 Lapse lapse acquisition	08/01/2013 Not done
Go no-go on time lapse acquisition	09/01/2013 Not done

Summary

- Forward modeling geophysical response exploration
- New joint inversion algorithms for exploration
- New fully coupled inversion algorithms for monitoring
- Forward modeling for reservoir temperature monitoring
- Test of the inversion at Stromboli
- Acquisitions at Jersey Valley (Nevada)
- New acquisitions Upper Arkansas Valley (CO)
- Field camp at Pagosa Springs (CO)
- New method of time lapse geophysics
- New method to monitor fracking







Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
1/1/2012	12/31/2012	1/1/2012	12/31/2012

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
255,586	21,000 ORMAT 24,000 CSM		220,447 +21,000 +24,000		Phase II 181,522

Timeline: 9/30/2011 to 12/31/2014

– Budget
  - Phase 1 (9/30/2011 to 12/31/2012) $255,586
  - Project total cost(9/30/2008 to 2/28/2012) $635,000

– Partner ORMAT Technologies Inc. Cost Sharing : $151,000

Phase 1	$21,000
Phase 2	$85,000
Phase 3	$45,000