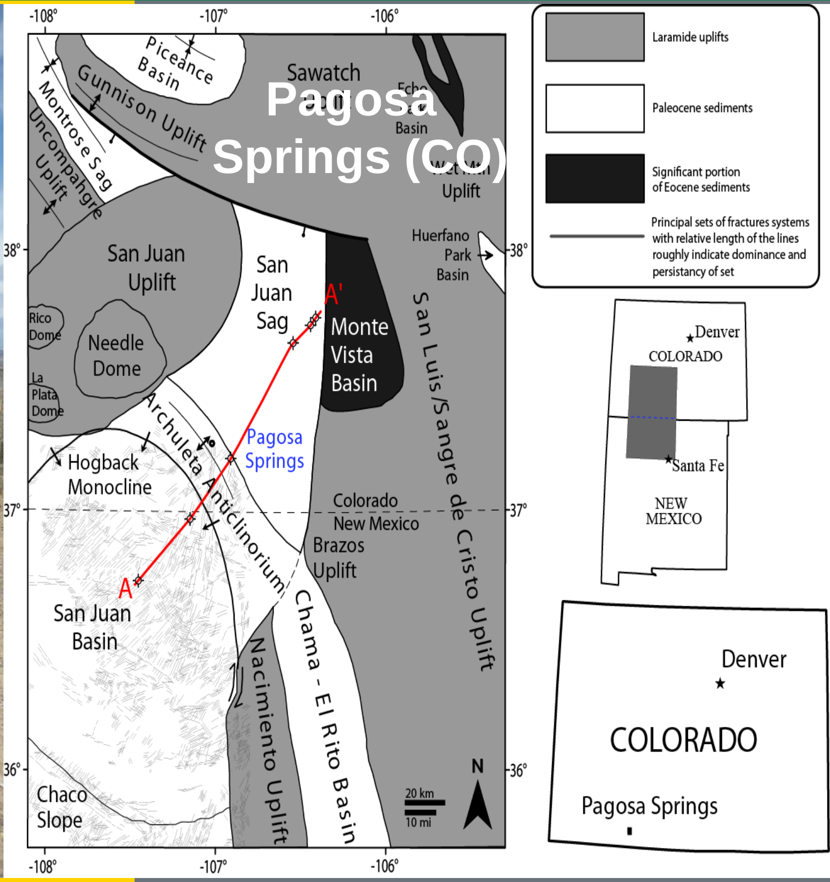
Geothermal Technologies Office 2015 Peer Review

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

Jersey Valley (NV)

Pagosa Springs (CO)



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 & Mike Batzle (Colorado School of Mines)

Ezra Zemach (ORMAT)

Objectives of the project

- Geologically-constrained geophysical inversion + specific attributes
- Joint inversion (stochastic/deterministic) for ground water flow imaging
- Combined passive and active geophysical methods+time lapse
- Application to Pagosa Springs to explain the plumbing system
- Application to Jersey Valley (Nevada, 10 MW) to reinject water

Impact on costs (consistent with Geothermal Technologies Office's goals)

- Decrease of the costs of drilling through better characterization of 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 exploration/production (see issue with the reinjection of water at Jersey Valley, NV)

Scientific/Technical Approach

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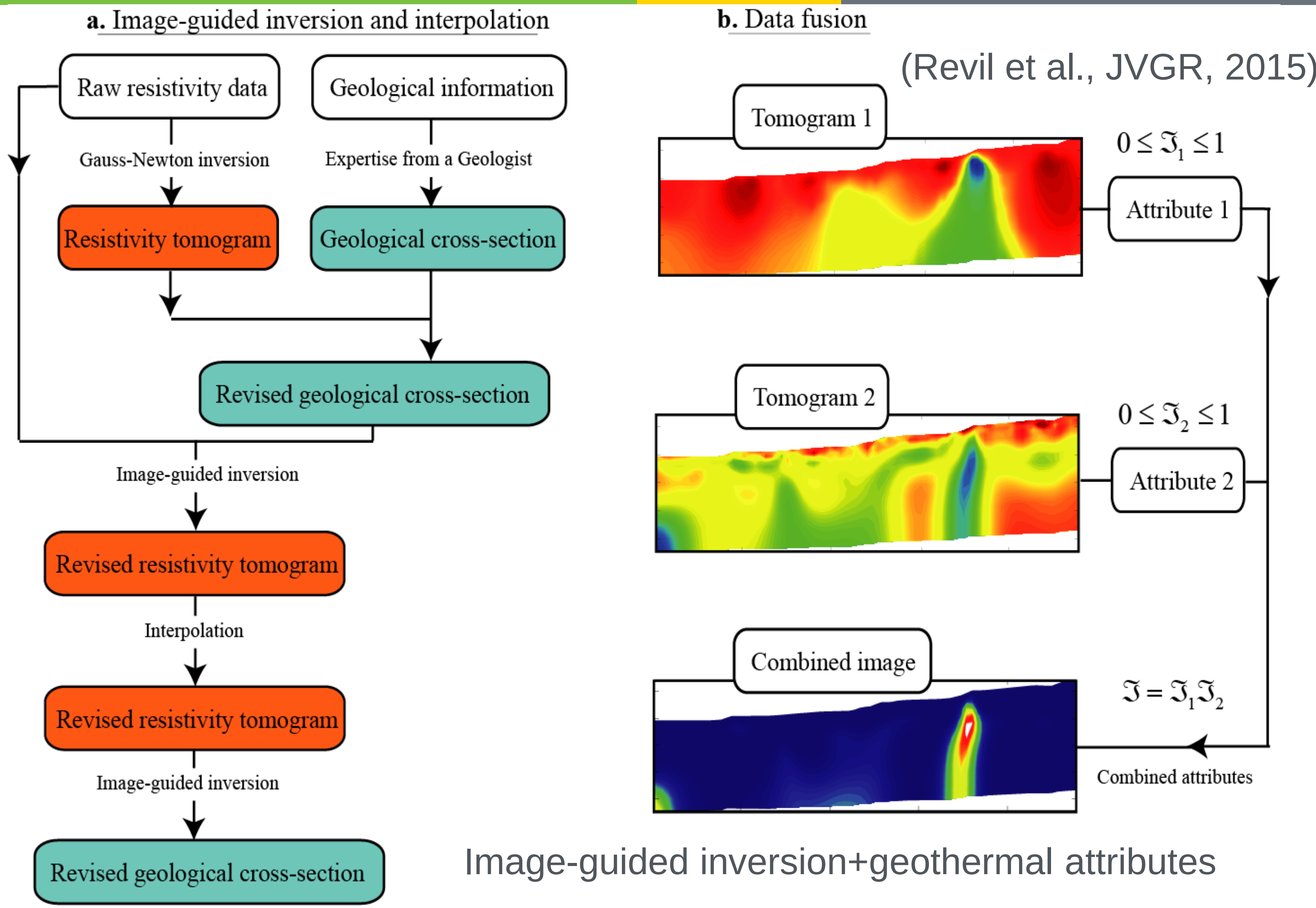
PHASE 1
(2011-2013)

Task 1 Assemble & Assess Data (Stromboli, Pagosa, Jersey)
Task 2 Formulate Joint Inversion Model
Task 3 Establish Database
Task 4 Rock Samples Gathered from Jersey Valley
Task 5 Testing of the Electromagnetic System
Task 6 Acquisition Planning (Pagosa + Jersey)

PHASE 2
(2014-2015)

Task 7/13 Permitting
Task 8 Utilize Jersey Valley Data in Initial Inversion
Task 9 Jersey Valley Data Set 1)
Task 10 Joint inversion of Jersey Valley data set 1
Task 11 Interpret inversion results with geologic information provided
Task 12 Acquisition Planning
Task 14 Second Joint Inversion Model for Jersey Valley
Task 15 Collect Jersey Valley Data Set 2
Task 16 Joint inversion of Jersey Valley Data 2
Task 17 Interpret inversion results w/geologic information
Task 18 Commercialization
Task 19 Document Software for Public Release

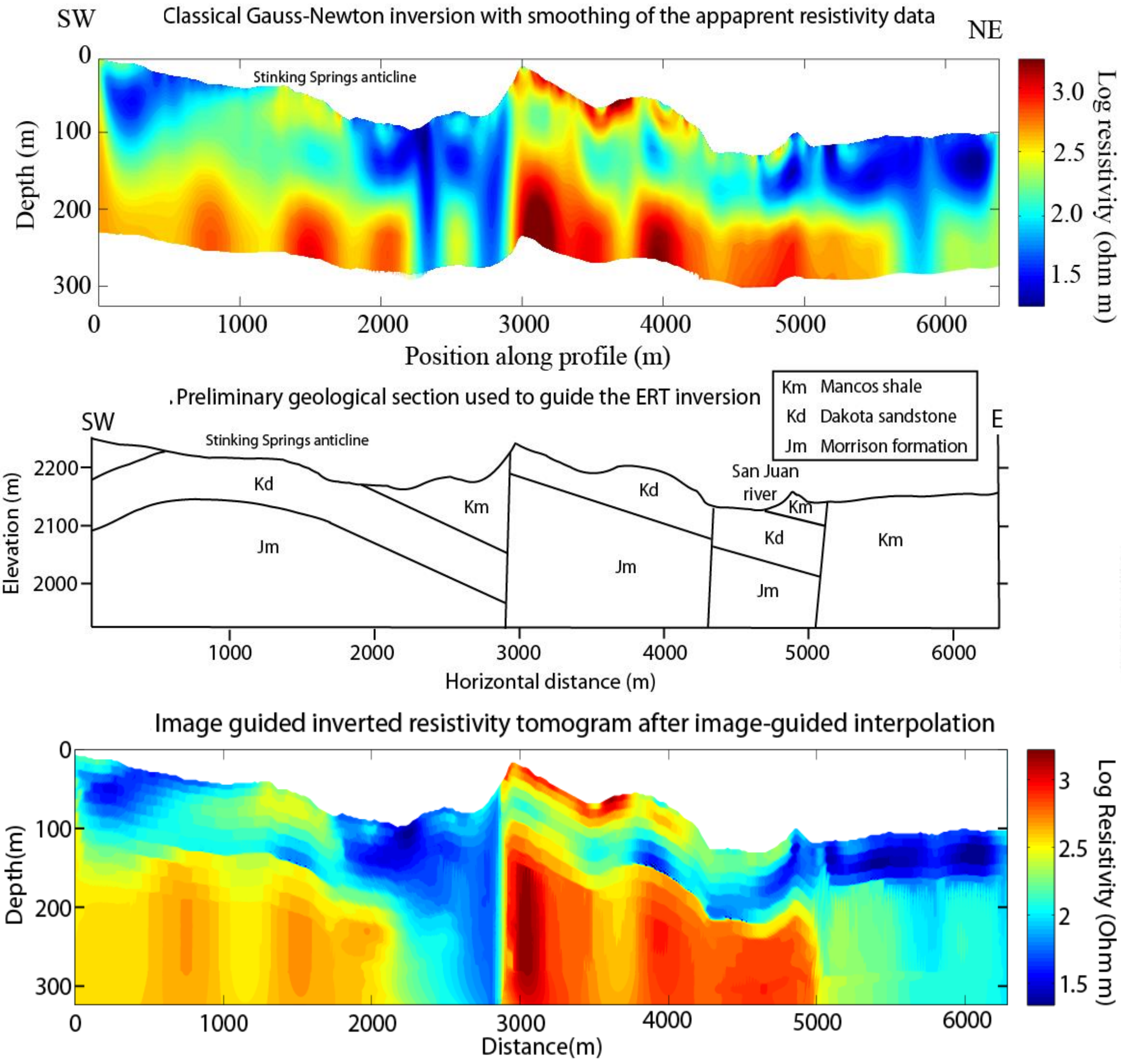
Scientific/Technical Approach



(Revil et al., JVGR, 2015)

Image-guided inversion+geothermal attributes

Scientific/Technical Approach



Application to Pagosa Springs (CO)

(Zhou et al., GJI, 2014)

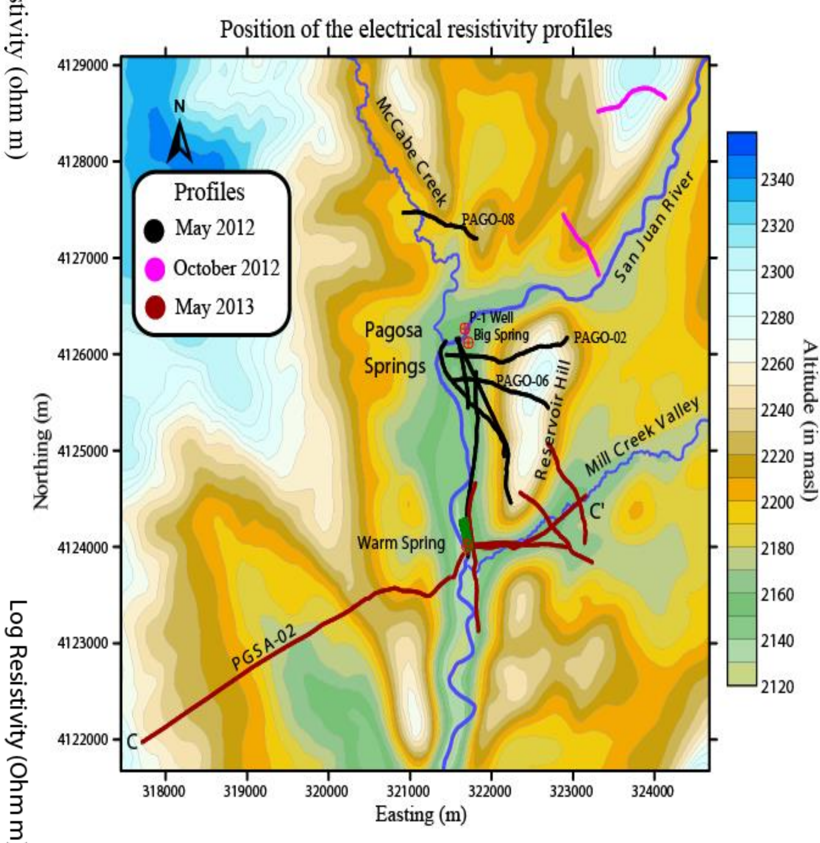
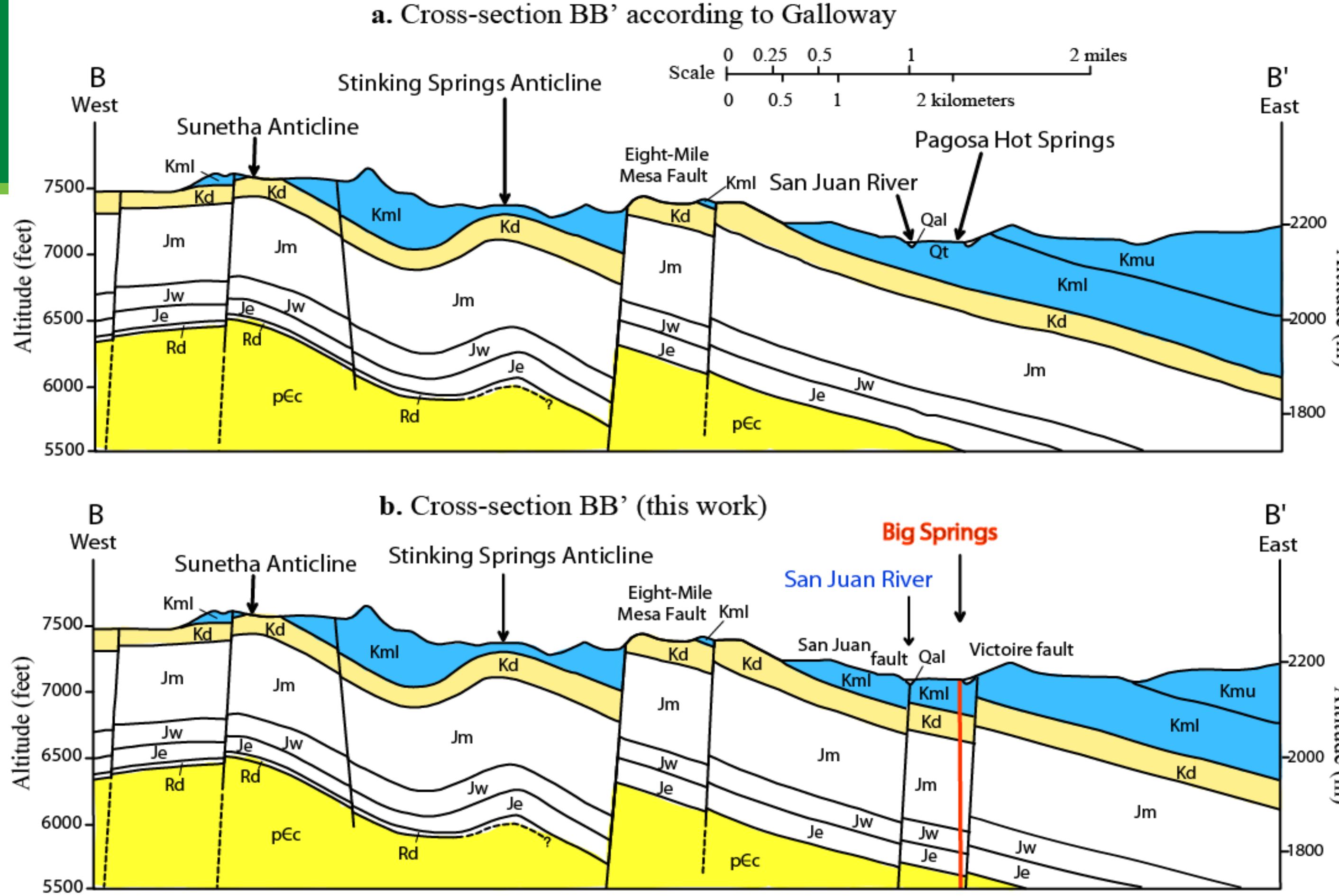


Image-guided inversion: Improved tomograms and updated geological models

S/T Approach

Initial geology

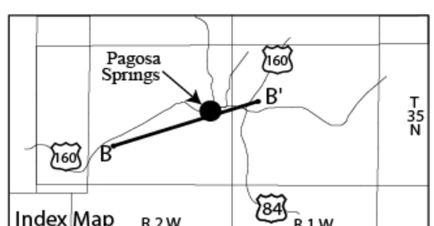
Updated geology

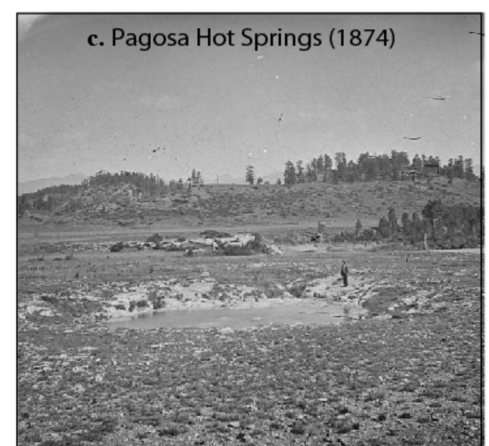


Definition of new faults Not visible at the surface because of the Mancos shale

Explanation

Qa - Alluvium, Quaternary
Qt - Travertine, Quaternary
Kmu - Mancos Shale (upper), Upper Cretaceous
Kml - Mancos Shale (lower), Upper Cretaceous
Kd - Dakota Sandstone, Upper Cretaceous
Jm - Morrison Formation, Upper Jurassic
Jw - Wanaka Formation, Upper Jurassic
Je - Entrada Formation, Upper Jurassic
Rd - Dolores Formation, Upper Triassic
pЄc - Crystalline Rocks, Precambrian

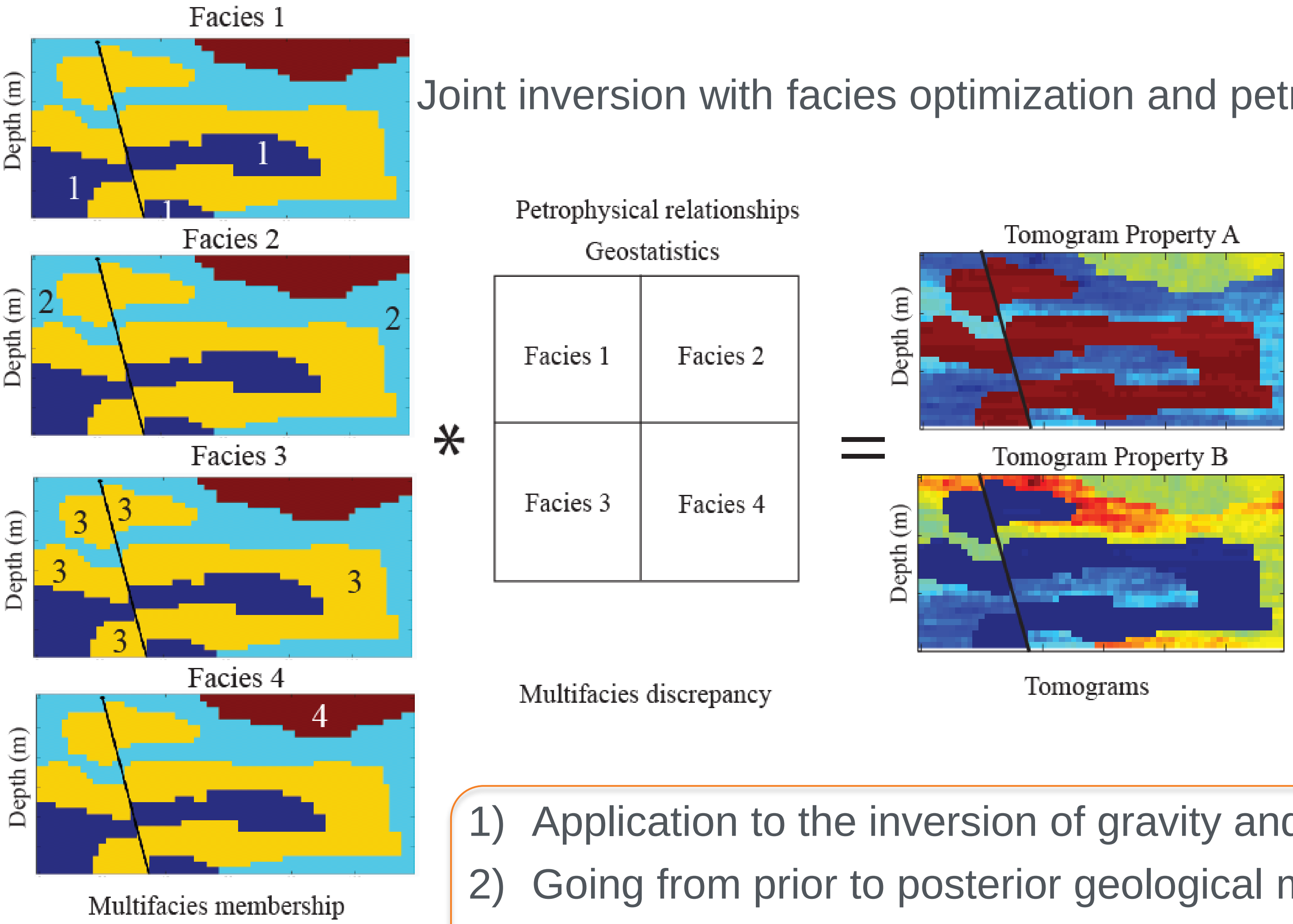



c. Pagosa Hot Springs (1874)

Pagosa Springs (CO)

Geologically-constrained geophysical inversion

Joint inversion with facies optimization and petrophysical clustering



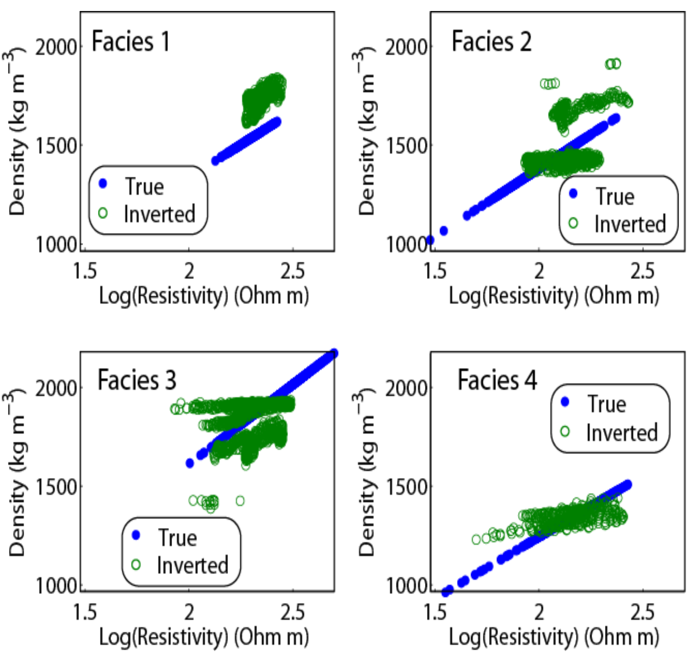
+ Updated geology

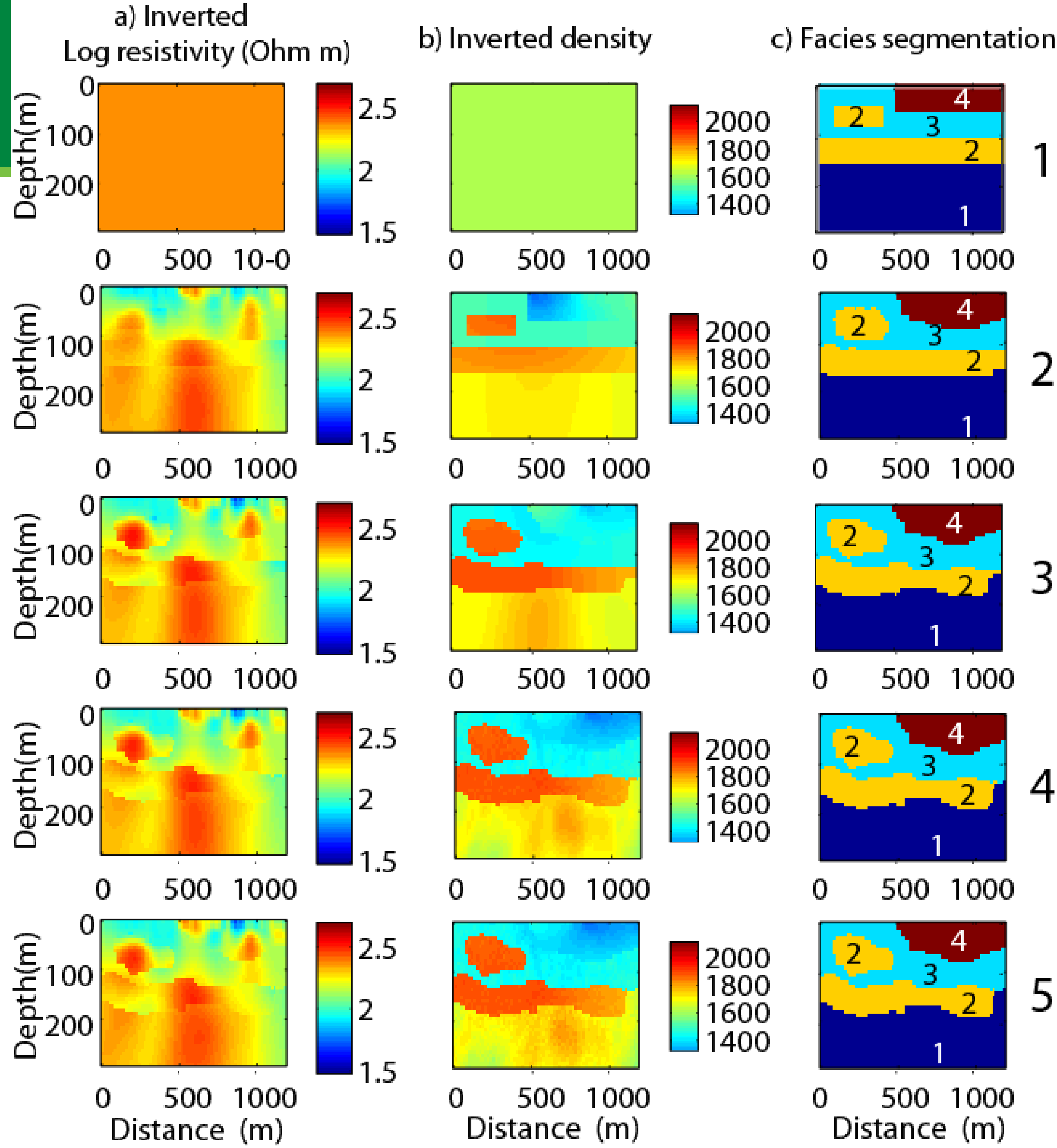
1) Application to the inversion of gravity and resistivity (MT)
2) Going from prior to posterior geological models (faults, facies)
3) Can be used with normalized attributes to refine targets

Scientific/Technical Approach

Joint inversion of Gravity and resistivity (galvanometric / MT)

Petrophysical clustering



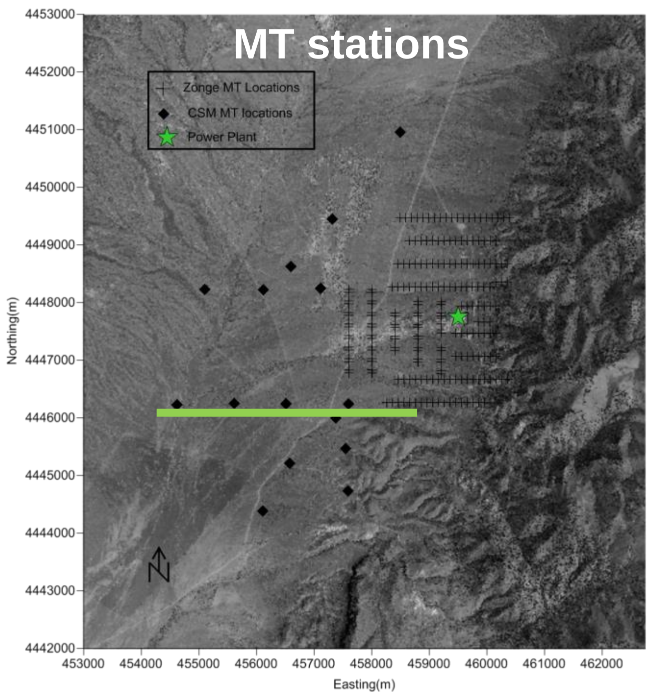


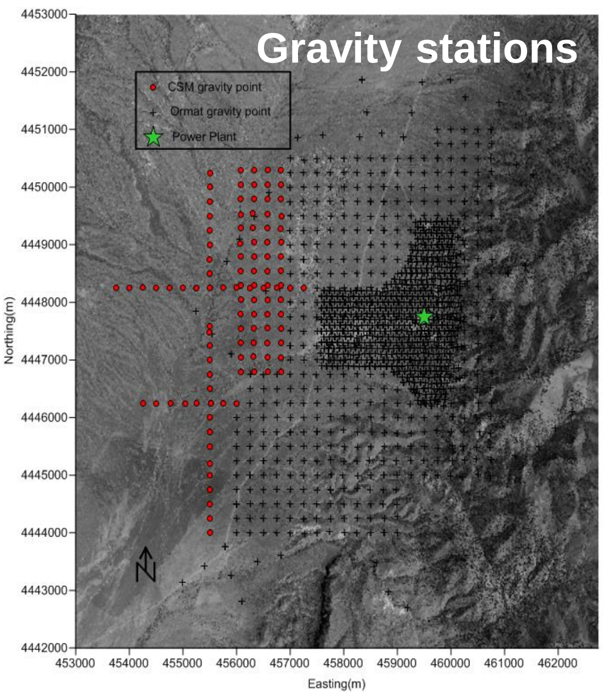
Limitation: Only 2D so far !

Work submitted to “Geophysics”

a) Develop a new approach for the time-lapse joint inversion of geophysical data: Done
b) Develop a preliminary technique of image-guided inversion of geophysical data: Done
c) Develop geologically-constrained joint inversion using the level set technique: Done
d) Perform the 3D tomography of Stromboli using gravity and resistivity data: Done
e) Large-scale self-potential survey can be used to assess the geometry of a geothermal field: Done
f) Application to Pagosa Springs to understand its plumbing system : Done
g) Application to Jersey Valley to understand the hydrogeology & assist ORMAT: in progress

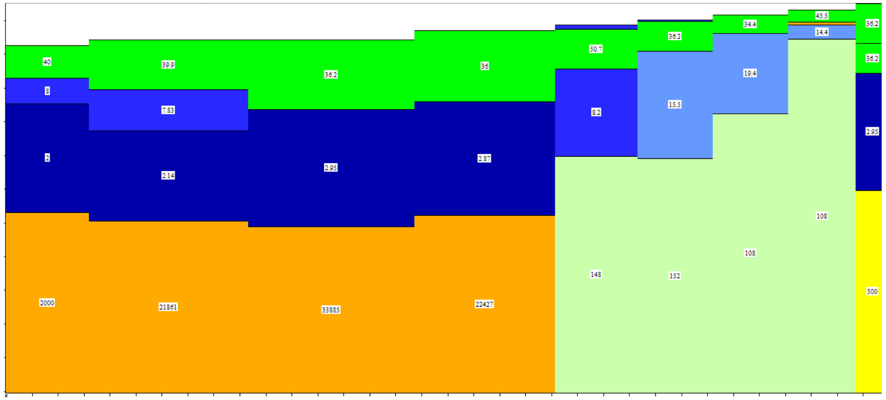
Jersey Valley (4 years ago and now)



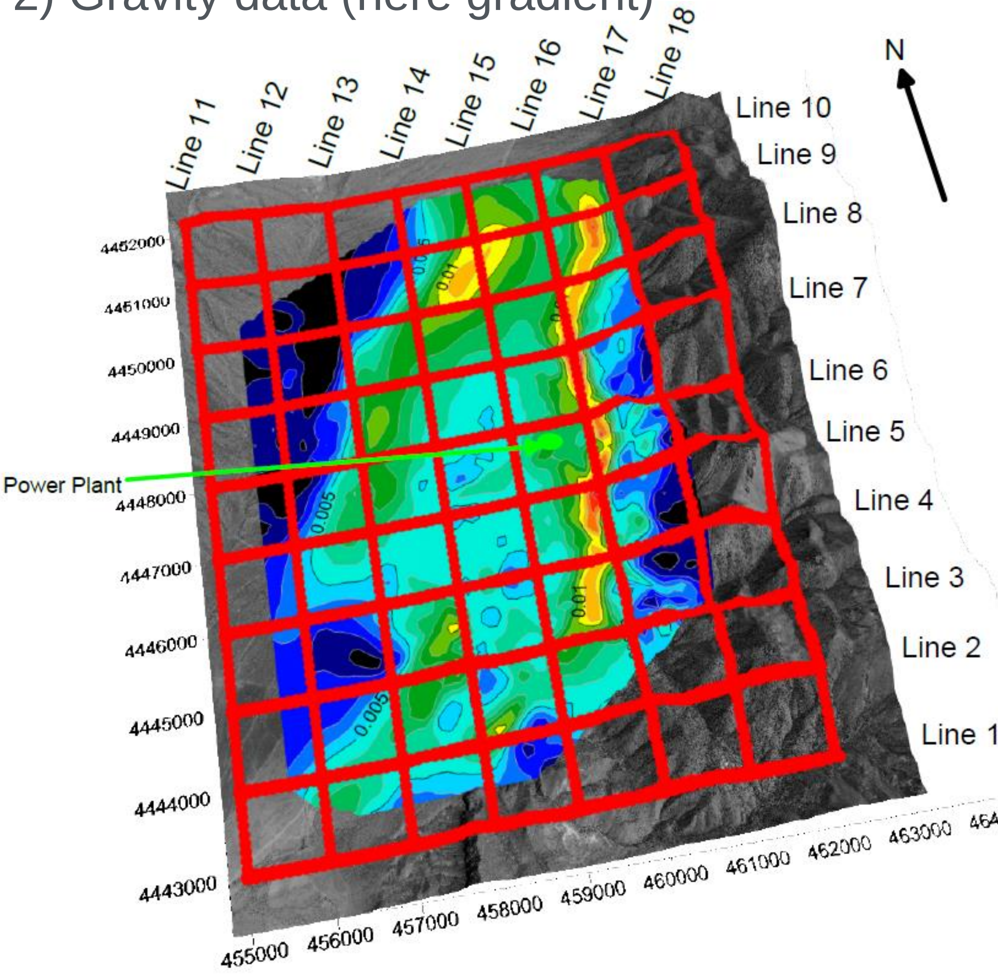


1210 gravity stations, and 221 MT stations

1) Magnetotelluric data



2) Gravity data (here gradient)



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3) Prior geological model

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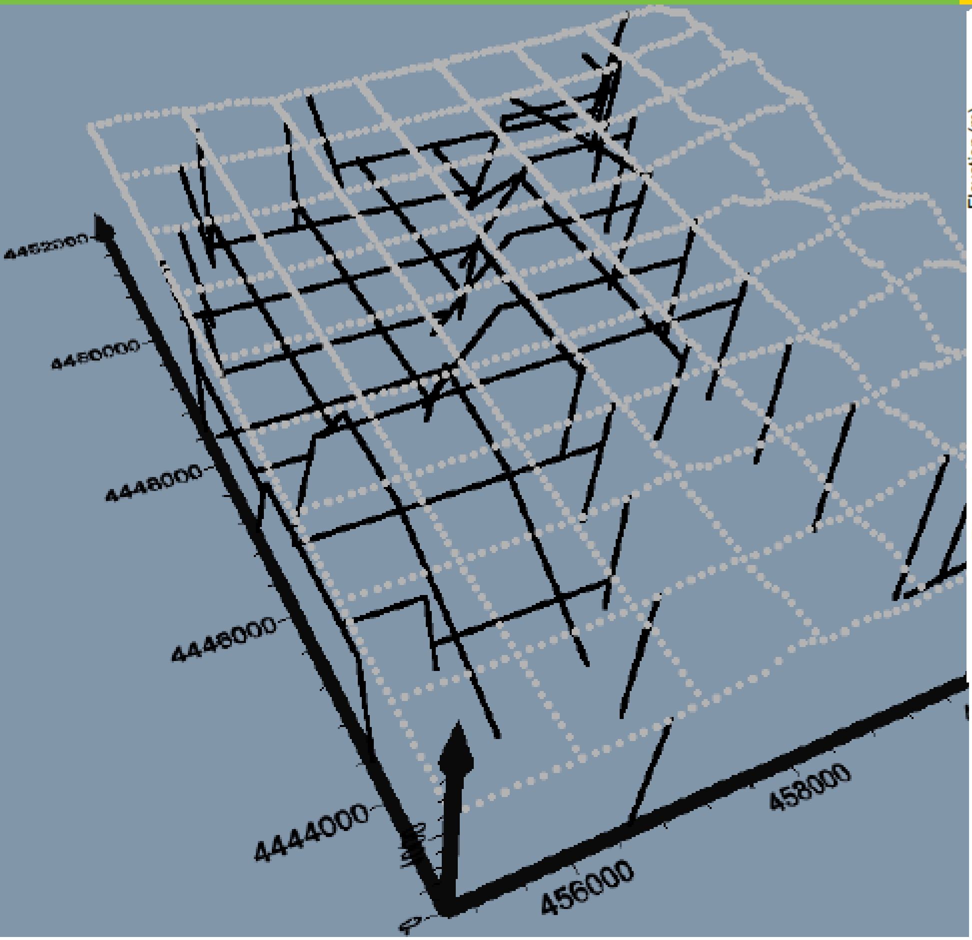
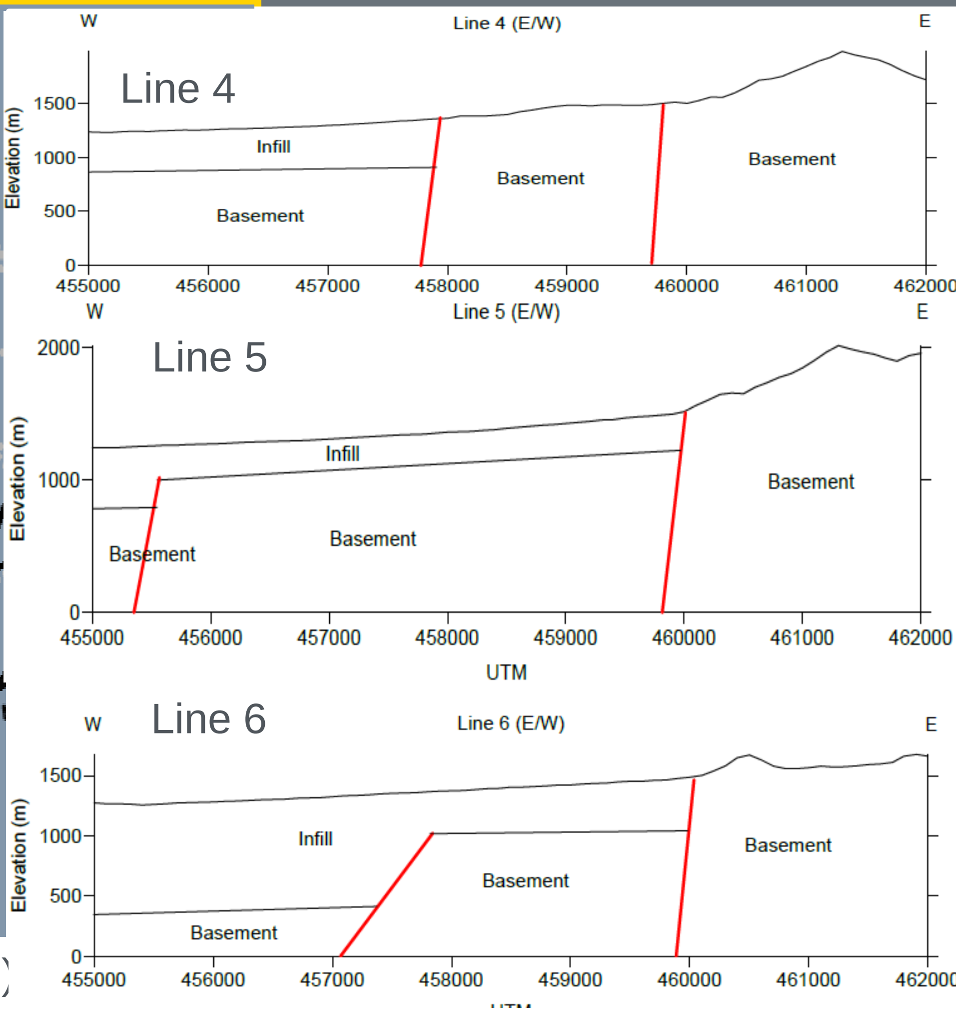
Updated geological model

The valley is bordered by a set of faults, which exhibit upward and downward flow

Accomplishments, Results and Progress



3D model (be used for ground water flow modeling)



18 profiles total to build a 3D model

1210 gravity stations, and 221 MT stations

Accomplishments, Results and Progress

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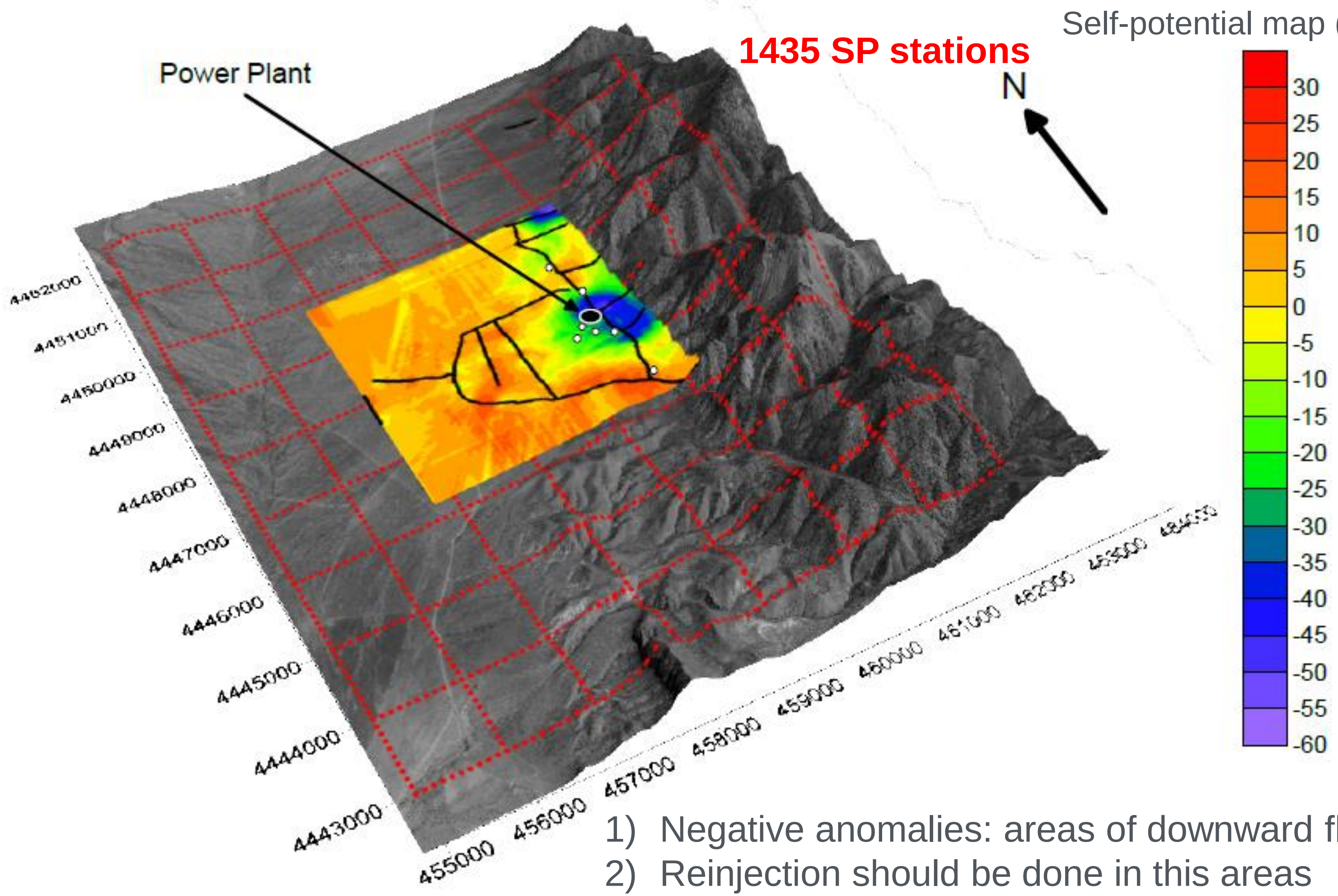

1) Negative anomalies: areas of downward flow
2) Reinjection should be done in this areas

Publications (11 peer-reviewed)

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1) Zhou J., A. Revil, **M. Karaoulis**, D. Hale, J. Doetsch, and **S. Cuttler**, Image-guided inversion of electrical resistivity data, Geophysical Journal International, doi:10.1093/gji/ggu001, 2014.

2) Revil A., et al., 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.

3) Linde N., L. Baron,T. Ricci, A. Finizola, **A. Revil**, et al., 3D density structure and geological evolution of Stromboli volcano (Aeolian Islands, Italy) inferred from land-based and sea-surface gravity data, Journal of Volcanology and Geothermal Research, 273, 58–69, 2014.

4) Zhang J., and **Revil, A.**, Joint inversion of geophysical data using petrophysical clustering and facies deformation, submitted to Geophysics.

5) Revil A., S. Cuttler, M. Karaoulis, J. Zhou, B. Raynolds**, and M. Batzle**, The plumbing system of the Pagosa thermal Springs, Colorado: Application of geologically-constrained geophysical inversion and data fusion, accepted for publication to Journal of Volcanology and Geothermal Research, 2015.

6) Soueid Ahmed, A., A. Jardani, **A. Revil**, and J.P. Dupont, SP2DINV: A 2D forward and inverse code for self-potential problems, Computers & Geosciences, 59, 9-16, 2012.

Award: A. Revil just received the Nishida award from Japan Geoscience Union

Future Directions

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May (1) Ground water flow model performed (steady state) (2) Computation of the associated self-potential field. (3) Perturbation of the ground water flow model consistent with the measured self-potential data. End of April and in preparation of the presentation for the DOE meeting in Westminster.

June (1) DOE meeting and presentation of the results. (2) Field camp of Geophysics at Pagosa Springs (3) Acquisition of additional data (mostly MT and gravity) at Pagosa Springs (see description in the last report) to demonstrate the proof of concept on another parget. (4) Final attempts to produce a geological model and a hydrogeological model consistent with all available geophysical data (SP, MT, gravity) and geological knowledge of the area. (5) Try to extend in 3D the codes.

July-August. (1) Finish and submit the last papers a) Stromboli (we never submitted the paper on Phase 1 regarding the 3D inversion of resistivity). b) Paper on the hydrogeology of Jersey Valley. (2) Finish the final report for DOE.

Milestone or Go/No-Go	Status & Expected Completion Date
End of the project	August 2015

Summary

- New techniques for the joint inversion of geophysical data
- Geologically-constrained geophysical inversion
- Self-potential can be used to track ground water flow
- Normalized attributes to delineate geothermal targets

- Successful application to volcanic systems (Phase 1)
- Delineation of the plumbing system of Pagosa Springs
- Determination of upflow/downflow in Jersey Valley