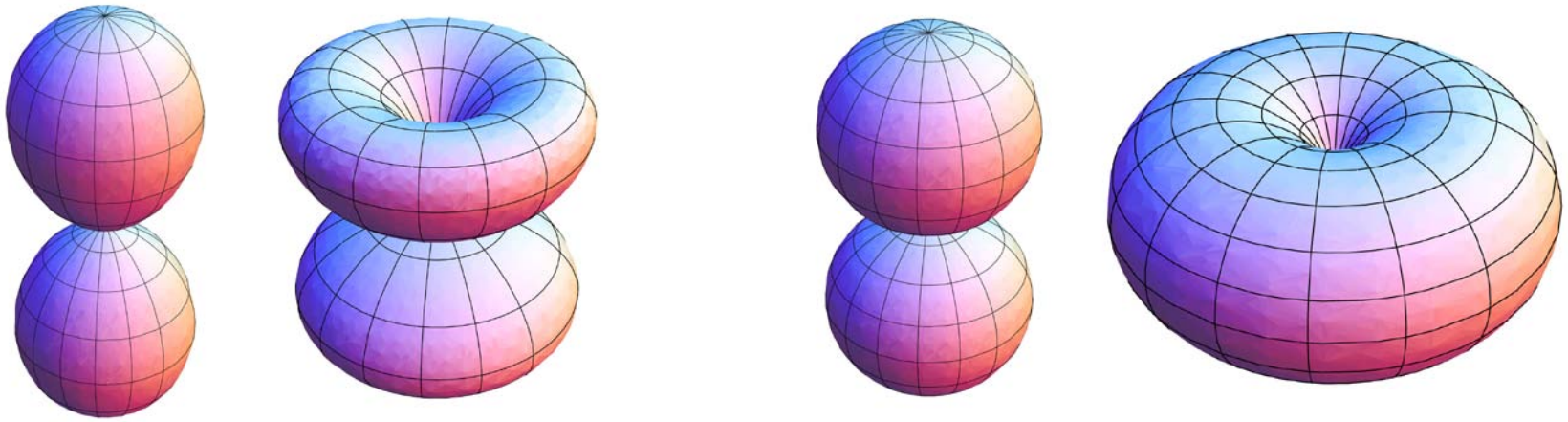


Microearthquake Technology for EGS Fracture Characterization

May 19, 2010

Principal Investigator: Gillian R. Foulger
Presenter: Bruce R. Julian
Foulger Consulting

Track Name

Mandatory Overview Slide

- Timeline:
  - Project start date: 1st January, 2009
  - Project end date: 31st December, 2012
  - Percent complete: 31%
- Budget:
  - Total project funding: **$703,040**
  - DOE share: $561,729
  - Awardee share: $141,311
  - Funding received in FY09: $117,039
  - Funding for FY10: $174,083
- Barriers:
  - Go/no-go points 7/31/3009, 6/30/2010 & 3/31/2011
- Partners:
  - Lawrence Berkeley National Laboratory
  - Magma Energy Corp.
  - U.S. Geological Survey
  - U.S. Navy
  - WesternGeco

Relevance/Impact of Research

Overall project objectives:

- To understand how EGS fracture networks develop
- To develop technology to determine accurate absolute three-dimensional positions of EGS fracture networks
- To understand the physical source processes of earthquake moment tensors
- To develop new technology for determining three-dimensional seismic wave-speed structures of reservoirs
- To transfer state-of-the-art micro-earthquake EGS technology to industry

Relevance/Impact of Research

Objectives for 2009:

Task	Foulger	Julian	Monastero	Sabin	Majer	De Luca	Hill	FY 2009 Month: CAL YR 2009 J F M A M J J A S O N D
Task 1: Application to test cases								
Coso	•	•	•	•				
The Geysers	•	•			•			
SE Geysers	•	•			•			
Desert Peak	•	•			•			
Geothermal Field "X", Indonesia	•	•				•		
Long Valley	•	•					•	
Hengill, Iceland	•	•						
Task 2: Methodological developments								★ go-no-go if location software development fails
Task 2.1: Earthquake locations	•	•						
Task 2.2: Earthquake source mechanisms	•	•						
Task 3: New technologies								
Regional earthquake tomography		•						
Application to datasets		•						
Task 4: Technology transfer to industry								
Oral presentations, reports etc	•	•						
Prep: "Guide to Micro-Earthquake Monitoring"	•	•						
Training course	•	•	•					
Reporting	•							

Relevance/Impact of Research

Impact:

- Accurate location of EGS fracture networks will guide successful targeted drilling
- Understanding of fracture type (shear, crack-opening/closure) will cast light on the physical nature of the fracture network created
- The results will increase the likelihood of drilling success, the most expensive element of exploration
- Innovations include:
  - Combination of absolute and relative earthquake locations
  - Selective waveform cross-correlation
  - Combination of local and regional earthquakes in tomography
  - Application to both natural and induced earthquake swarms

Scientific approach

- Development of software:
  - Portable ANSI C
  - Object-Oriented
  - Documentation: Tutorials, online reference manual, online help
- Components
  - High-resolution hypocenter location
  - Microearthquake source mechanisms
  - Local/Regional-earthquake tomography

Scientific/Technical Approach

- Application to data sets:
  - Coso geothermal field, California
  - The Geysers, California
  - Desert Peak, Nevada
  - A geothermal field in Indonesia
  - Long Valley caldera, California
  - the Hengill-Grensdalur geothermal area, Iceland
- Data sets already exist.
- Data have already been processed using more primitive techniques, so their suitability is assured.
- Several data sets are from currently producing fields, so the impact of the results on production may be assessed.
- The software developed will be applied to other DoE EGS projects, *e.g.*, the AltaRock Newberry project, Oregon.

Scientific/Technical Approach

- Milestones
  - Completion of absolute/relative earthquake location software: Target date 9/30/2009, Status: Achieved
  - Completion of selective waveform cross-correlation software: Target date 9/30/2009, Status: Achieved
  - Application of software to data from the Coso geothermal field : Target date 12/31/2009, Status: Achieved

- Go/No-go decisions
  - 2009: 7/31/2009 – earthquake location software – GO
  - 2010: 6/30/2010 – moment-tensor software – TBA

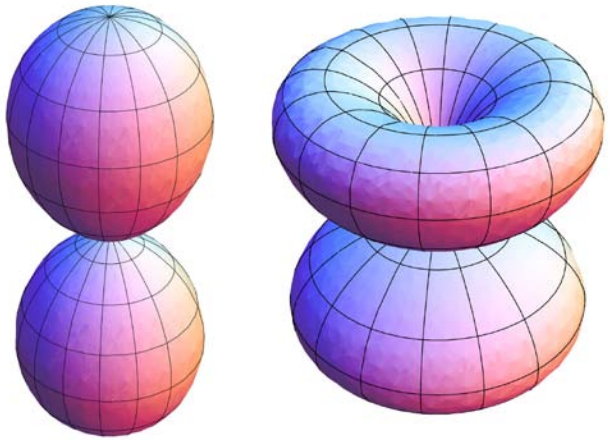
High-Resolution Hypocenter Location

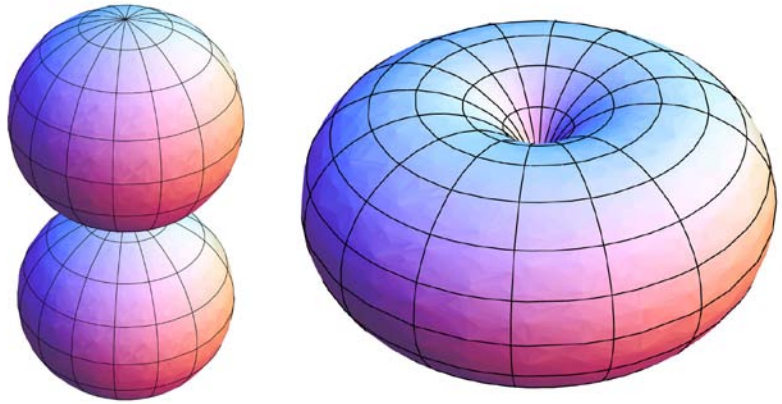
- Improve sensitivity to absolute locations (*hypocc*)
  - Add absolute arrival times to inverted data sets
  - Programmed, documented & tested
- Measure time differences from digital seismograms (*mkdtdat*)
  - Waveform data-base programmed, documented & tested
  - Waveform cross-correlation programmed, ready for testing

Microearthquake Source Mechanisms (*seismech*)

- Add net forces to earthquake source mechanisms

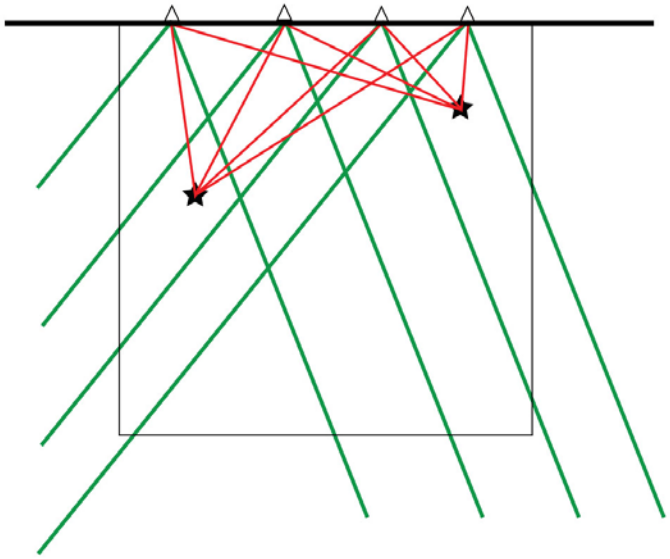
  – Linear programming inversion of polarities, amplitudes, amplitude ratios
  – Forward problem formulated, programmed & tested
  – Inverse problem formulated & programmed, ready to test





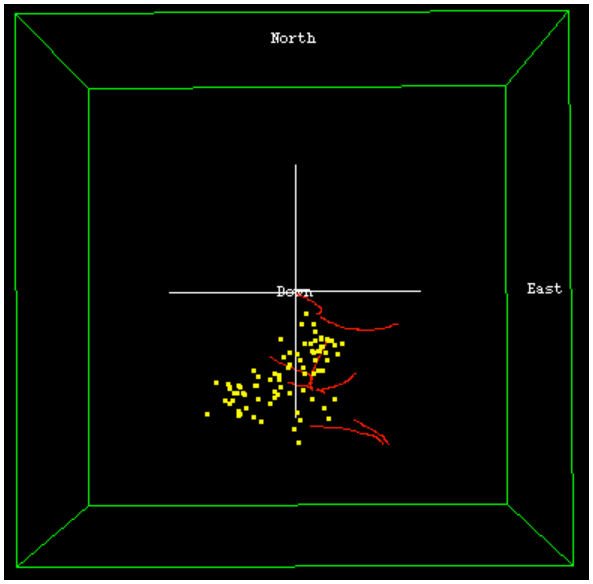
Local-Regional Earthquake Tomography (*tomo4d*)

- Use data from regional earthquakes
  - Solve for orientation/curvature of incoming wave fronts
  - Programming will begin 7/1/2010

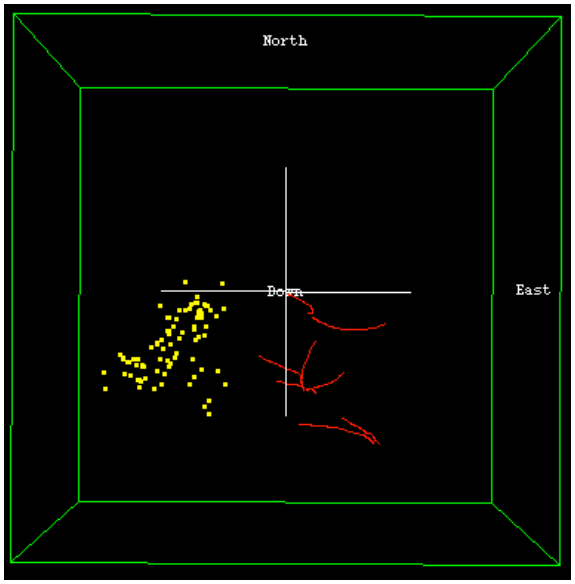


Application of *hypocc* with absolute constraints to data from Coso

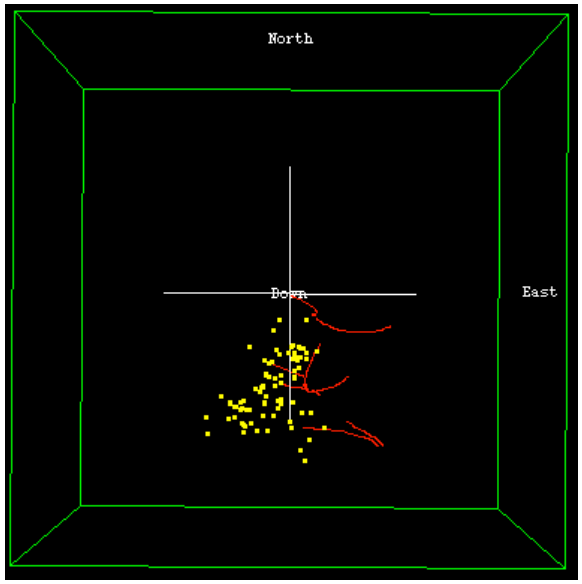
- February 2005 MEQs near injection well 34-9RD2



3 iterations



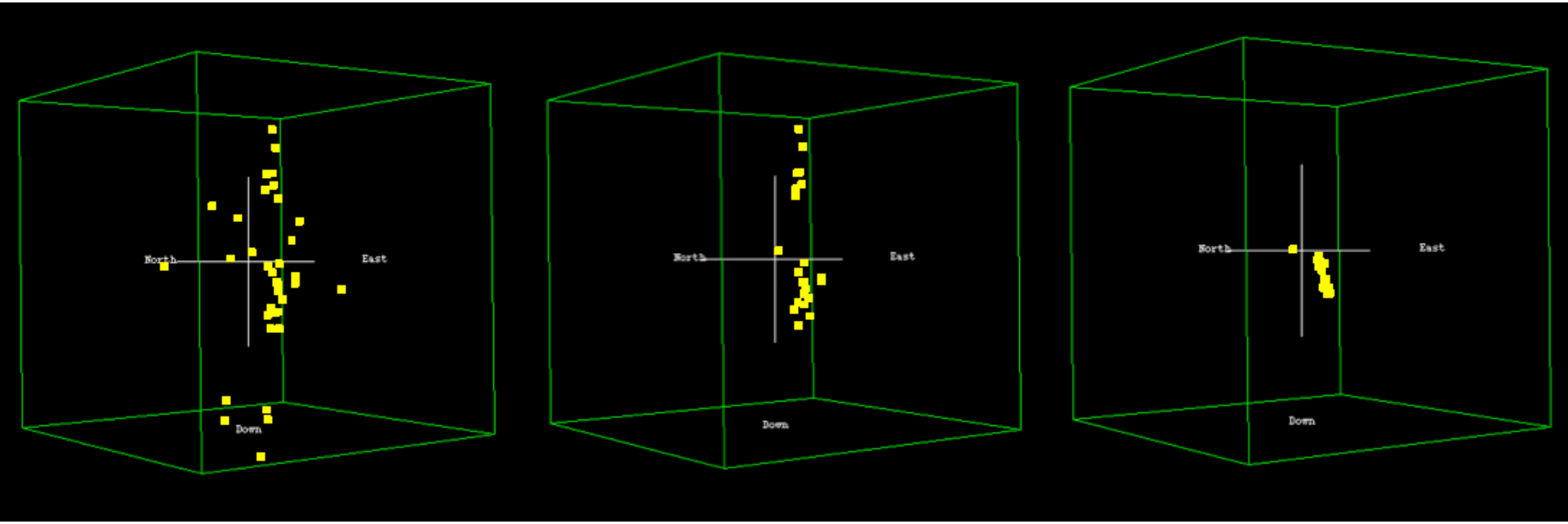
9 iterations



9 iter + absolute

hypocc with absolute constraints: Desert Peak

- Inclusion of absolute constraint allows more iterations



Original locs | *hypocc* 2 its | *hypocc* 30 its

Team qualifications, special facilities/equipment

- Programming, data analysis: Gillian R. Foulger & Bruce R. Julian
- Coso data: US Navy GPO/Dr. Andrew Sabin
- Geysers, Desert Peak data: USGS, Berkeley/Dr. Ernie Majer
- Indonesia data: Geosystem - WesternGeco/Dr. Luciana De Luca

UNIX-based Apple Mactinosh computers used for programming and data analysis

Project Management/Coordination

Management activities & approaches

Schedule

- Schedule clearly laid out in Gantt chart
- Applied strictly to pace the work
- Additional work incorporated, or work advanced if opportunistic, e.g., early processing of Desert Peak data

Application of resources

- Spending expected to be fairly uniform
- Resources largely for salary & dissemination of results (meetings, conferences)

Project Management/Coordination

Management activities & approaches

Integration with other projects in the program

- Close co-ordination with other projects (meetings, conference calls)
- Processing of data from Desert Peak advanced
- Major software packages will be ready in time for Newberry EGS project (AltaRock)

Coordination with industry & stakeholders

- Regular meeting presentations & proceedings papers. Recently:
  - Canadian Society of Exploration Geophysicists, October 2009: keynote talk given
  - Annual meeting of Geothermal Resources Council, Reno, October 2009
  - American Geophysical Union, San Francisco, December 2009
  - Stanford Geothermal Workshop, February 2010

Future Directions

Expected outcome & future research

- FY2010:
  - Complete moment-tensor software
  - Complete processing Hengill data
  - Commence processing Geysers data
  - Additional technology transfer at key meetings
  - Chair Special Session at Annual meeting of SEG, 17–22 October: *Microseismicity: Beyond dots in a box*
- FY2011:
  - Complete tomography software: Go/no-go point 3/31/2011
  - Commence testing tomography software
  - Apply location and moment-tensor software to data from Long Valley, California, & Indonesian geothermal field

Mandatory Summary Slide

Summary

- Project on schedule
- Results encouraging
- No major setbacks to date

FY2009	FY2010
Complete: relative/absolute location software	Complete: moment-tensor software
Complete: cross-correlation software	Start: tomography software
Start: processing Coso data	Start: processing Coso, Hengill, Geysers data
Technology transfer	Technology transfer

Supplemental Slides

Papers in peer-reviewed journals

1. Julian, B.R. and G.R. Foulger, Time-dependent tomography, accepted, *Geophys. J. Int.*

2. Julian, B.R., G.R. Foulger, F.C. Monastero and S. Bjornstad, Imaging Hydraulic Fractures in a Geothermal Reservoir, *Geophys. Res. Lett.*, **37**, L07305, 10.1029/2009GL040933

3. Tkalcic H., D. S. Dreger, G. R. Foulger and B. R. Julian, The puzzle of the Bardarbunga, Iceland earthquake: No volumetric component in the source mechanism, *Bull. Seismol. Soc. Am.*, **99**, 3077-3085, 2009.

Conference abstracts

1. Petty, S., T. Cladouhos, G.R. Foulger, B.R. Julian & M. Fehler, Induced seismicity and geothermal energy, 34th Geothermal Resources Council Annual Meeting, Sacramento Convention Center, Sacramento, California, October 24-27, 2010 .

2. Julian, B.R., G.R. Foulger, Improved Methods for Mapping Permeability and Heat sources in Geothermal Areas using Microearthquake Data, Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 1-3, 2010.

3. Julian, B.R., G.R. Foulger, Resolving seismic moment tensors with body-wave amplitude ratios, *EOS Trans. AGU*, Fall Meet. Suppl., Abstract S21B-1720, 2009.

4. Tkalcic, H., D.S. Dreger, G.R. Foulger, B.R. Julian, A. Fichtner, A seismological portrait of the anomalous 1996 Bardarbunga volcano, Iceland, earthquake (invited poster), *EOS Trans. AGU*, Fall Meet. Suppl., Abstract S21B-1710, 2009.

5. Foulger, G.R., Microearthquake Analysis Techniques For Geothermal Applications, *EOS Trans. AGU*, Fall Meet. Suppl., Abstract S32B-02 (invited), 2009.

Conference abstracts (continued)

6. Foulger, G.R., Microearthquake seismology: Cinderella technology coming into its own, invited paper presented at the Canadian Society of Exploration Geophysicists (CSEG) Microseismic Workshop, Calgary, Canada, 13-15 October, 2009.

7. Foulger, G.R. and B.R. Julian, Applied Microearthquake Techniques for Geothermal Resource Development, Proceedings, conference on *Faulting and seismicity in the lithosphere: tectonophysical concepts and effects* held on the 60th anniversary of the Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences, and 30th anniversary of the Laboratory of Tectonophysics, Irkutsk, Siberia, Russia, August 17-22, 2009.

8. Julian, B.R. and G.R. Foulger, Non-Double-Couple Earthquake Mechanisms, Proceedings, conference on *Faulting and seismicity in the lithosphere: tectonophysical concepts and effects* held on the 60th anniversary of the Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences, and 30th anniversary of the Laboratory of Tectonophysics, Irkutsk, Siberia, Russia, August 17-22, 2009.

9. Foulger, G.R. and L. De Luca, Detailed image of fractures activated by a fluid injection in a producing Indonesian geothermal field, *Thirty-Fourth Workshop on Geothermal Reservoir Engineering,* Stanford University, Stanford, California, February 9-11, 2009.

10. Julian, B.R., G.R. Foulger and F.C. Monastero, Seismic Monitoring of EGS Stimulation Tests at the Coso Geothermal Field, California, Using Microearthquake Locations and Moment Tensors, *Thirty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, February 9-11, 2009.

Conference abstracts (continued)

11. Julian, B.R. and G.R. Foulger, Time-Dependent Seismic Tomography of Geothermal Systems, *Thirty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, February 9-11, 2009.

12. Julian, B.R. and G.R. Foulger, Monitoring Geothermal Processes with Microearthquake Mechanisms, *Thirty-Fourth Workshop on Geothermal Reservoir Engineering, Stanford University*, Stanford, California, February 9-11, 2009.