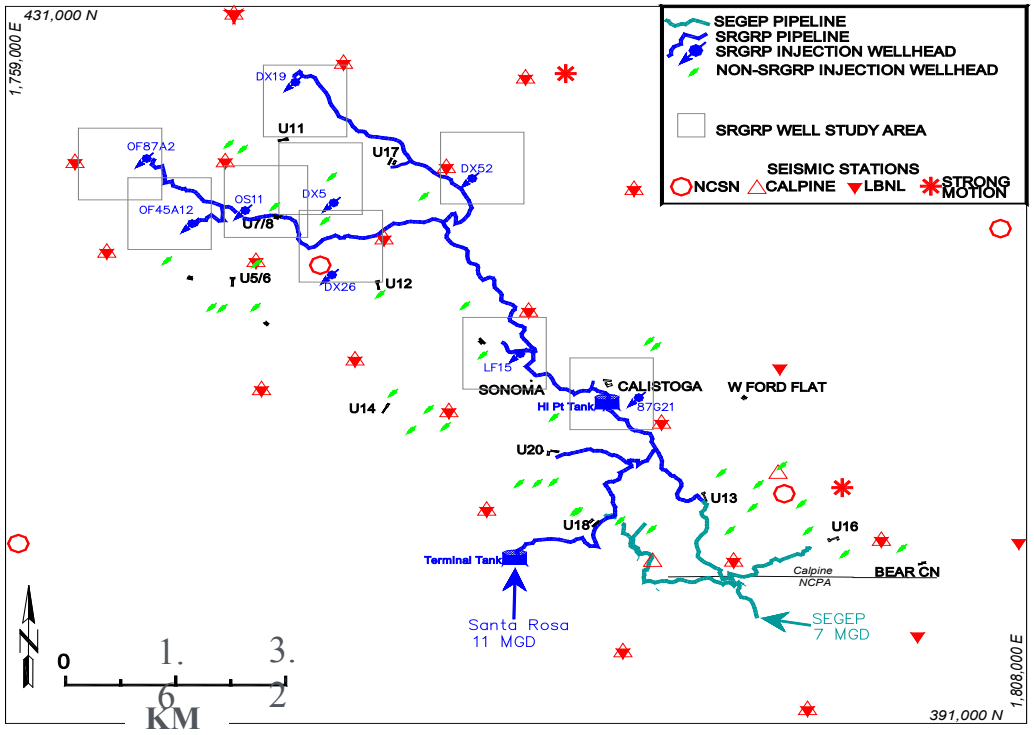


Monitoring the Effect of Injection of Fluids from the Lake County Pipeline on Seismicity at The Geysers, California Geothermal Field

May 19, 2010

Ernest L. Majer

LBNL

Seismicity and Seismic

Overview

- Timeline
  - Start: Oct 2, 2009
  - End: Sept 30, 2014
  - 10% complete
- Budget
  - Total project funding: $1,451,832 (over 5 years)
  - DOE share: $1,176,832 (FY 10 = $250K)
  - Awardee share: $275,000 (FY 10 = $75K)
  - No funding was received in FY09
  - Funding for FY10: Note, all funding was received in FY10 to be spread over 5 years
- Barriers
  - Reservoir Validation Barrier
    - Barrier I: Images of Fractures After Stimulation – Inability to characterize the physical parameters of potential EGS reservoirs after stimulation
  - Reservoir Scale Up Barrier
    - Barrier L: Well Field Design – Inability to assess and select the most efficient well-field design
  - Long-Term Sustainability
    - Barrier M : Unknown ability to manage long-term rock temperature, transmission, fluid quantity and fluid chemistry
- Partners
  - Calpine, the county of Lake, CA, NCPA

Relevance/Impact of Research

Objectives:

1. Upgrade and continue operation of a high resolution seismic array for five years at The Geysers as well as expand the array to record seismicity from any new additional DOE EGS sites at The Geysers as they come on line. The data will be archived and made available to the public through the USGS Northern California Data Center (NCDC).
2. To use microearthquake monitoring to understand and intelligently manage the effects of fluid injections and stimulations to aid in the optimization of Enhanced Geothermal Systems (EGS).

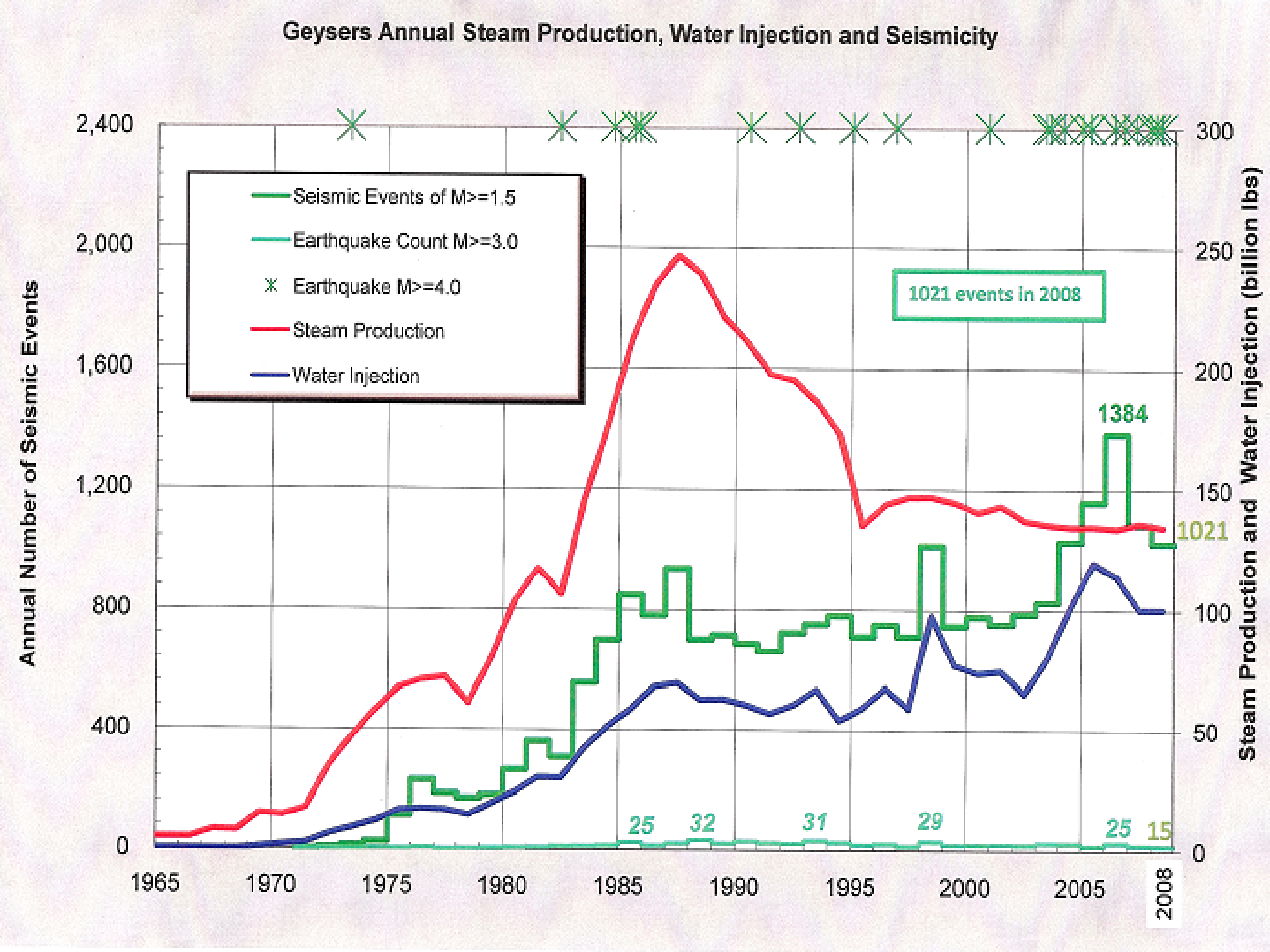
Relevance/Impact of Research

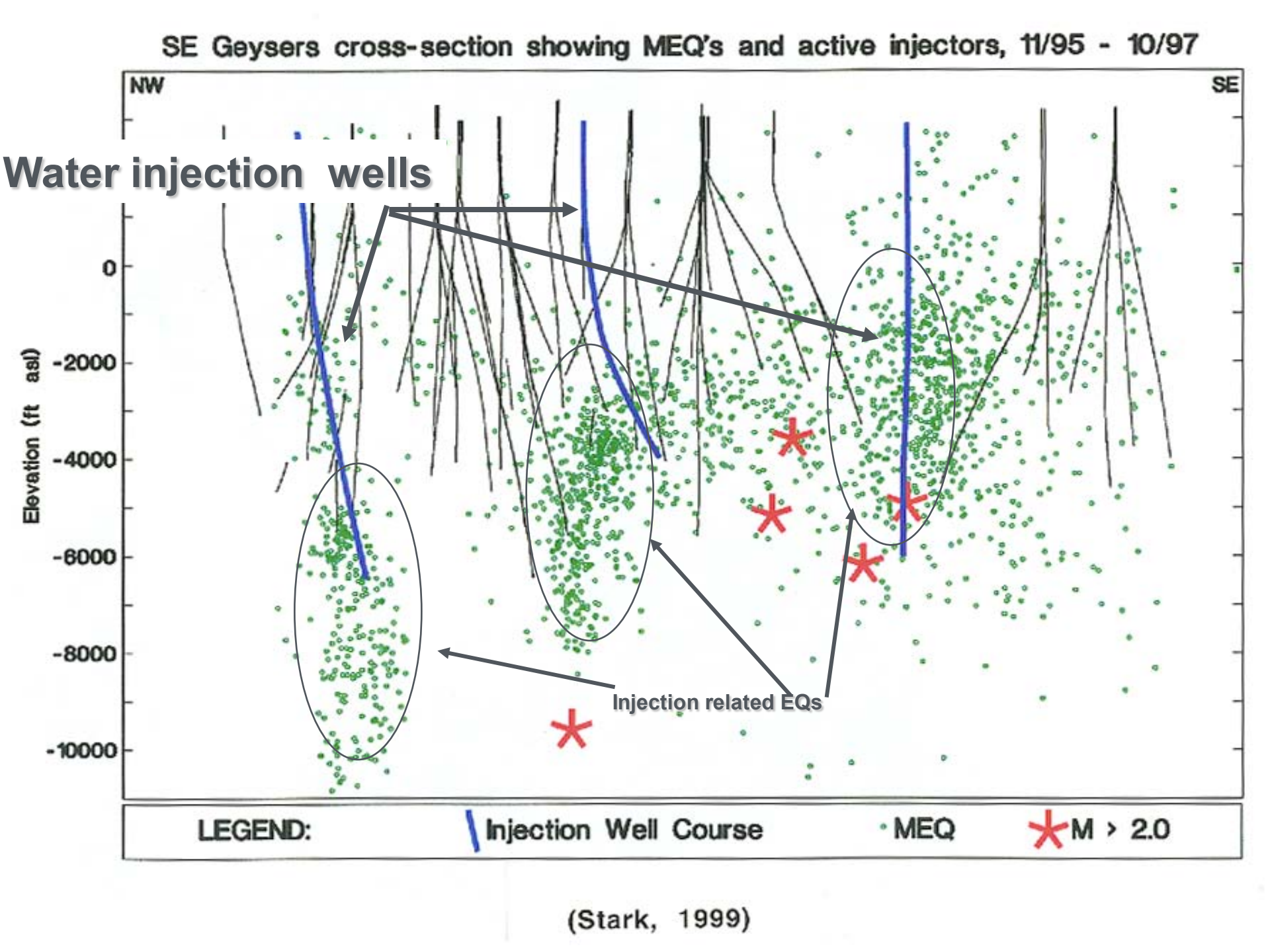
- The Geysers is the world's largest geothermal field that has a very large untapped thermal resource
  - Reservoir enhancement is expected to significantly expand resource output
  - Current operators use MEQ data for understanding reservoir dynamics and managing injection effects (impact of seismicity on surrounding communities)
- This project will therefore:
  - Satisfy the requirements to provide detailed real-time monitoring, via an independent institution, to the public and scientific community
  - Provide data to the operators for managing injection rates for reservoir validation, performance and expansion by using MEQ data and analysis
  - Perform research to advance the understanding between fluid injection/withdrawal and MEQs to optimize reservoir performance

Relevance/Impact of Research

Innovative aspects of project.

- High resolution (500 SPS), high dynamic range (24 bit), multi-component (3-C) large aperture dense array (potentially 36 stations, ~0.5 km between stations) for data collection.
- Data will be provided in 3-D and real time to public and scientific community
- Research results meant to be integrated with operations for rapid decision making for reservoir optimization
- Continuous operation over a 5 year time period to examine short and long term reservoir changes and response to injection/production


Geysers Annual Steam Production, Water Injection and Seismicity
Annual Number of Seismic Events
Steam Production and Water Injection (billion lbs)
Seismic Events of M>=1.5
Earthquake Count M>=3.0
Earthquake M>=4.0
Steam Production
Water Injection
1021 events in 2008
1384
1021
25
32
31
29
25
15
2,400
2,000
1,600
1,200
800
400
0
300
250
200
150
100
50
0
1965
1970
1975
1980
1985
1990
1995
2000
2005
2008


SE Geysers cross-section showing MEQ's and active injectors, 11/95 - 10/97
NW
SE
Water injection wells
0
-2000
-4000
-6000
-8000
-10000
Elevation (ft asl)
Injection related EQs
LEGEND:
Injection Well Course
MEQ
M > 2.0
(Stark, 1999)

Interesting observations at The Geysers

- Large events happen (sometimes) at the edges of the reservoir/after the injection stops
  - Implication of diffusion processes
- Variable rate dependency of injection versus seismicity
  - Sometimes anti-correlation between injection and seismicity
- Seismicity reaches an equilibrium (in certain magnitude ranges)
- Seismicity does not follow normal aftershock patterns
- Thermal effects seem to play a dominant role
- Close relation between seismicity and volume balance
  - Implies volume change, not volume injected, is important
- Variable relation between foreshocks, aftershocks, b-values, etc.
- Induced seismicity appears to change mechanisms (triggering) over magnitude ranges

Scientific/Technical Approach

- Task 1 Data Collection
  - Array upgrade and expansion
    - FY 10
      - "Rehabilitate" current array
      - Add six stations to include new injection and production projects
      - Add strong motion instrument to NW Geysers
      - Integrate Alta Rock 8-station borehole array to field wide array (still in negotiation)
      - Provide data to NCDC (auto-locations, magnitudes, waveforms)
    - FY 11 to end of project
      - Continuous operation
      - Add stations as Geysers field expands (within budget)

Scientific/Technical Approach

- Task 2 Research on Seismicity and Injection/Production
  - Examination of “donut hole”
    - FY 10
      - Relocate 4 years of data (113,000 events > Mag 0)
        - » 1-D model
        - » Tomo DD (3-D)/correlation analysis
      - Examine wave propagation effects (disappearing S-wave)
      - Moment/Focal mechanisms
      - Apply 3-D visualization (VISIT)
      - Correlate seismicity data with injection production/data in NW Geysers (support Calpine EGS project)
        - » Add B-value variation
        - » Event evolution/properties in time and space
        - » Correlate with EGS injections (may not occur until FY 11)

Scientific/Technical Approach

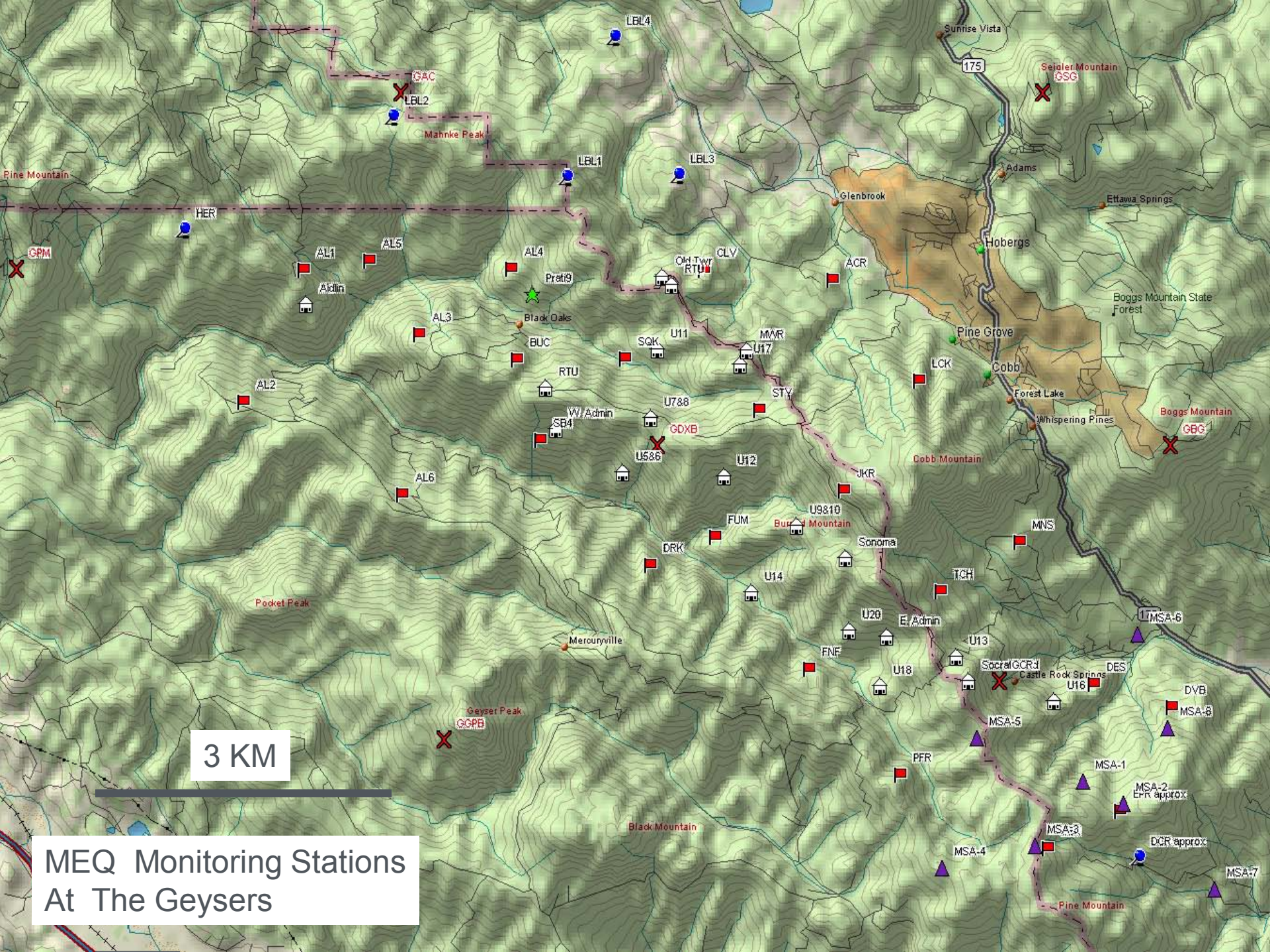
- Task 2 Research on Seismicity and Injection/Production
  - **FY 11 to end of project**
    - Continue above analysis in a time lapse mode
    - Examine different candidate MEQ mechanisms
      - » Thermal effects
      - » Pressure effects
      - » Volume changes
      - » Chemical
      - » Combined
    - Focus on selected parts of the field as injections change
    - Correlate with Calpine/NCPA/Other operators characterization data

Task 1 Data Collection/Array Upgrade and Expansion

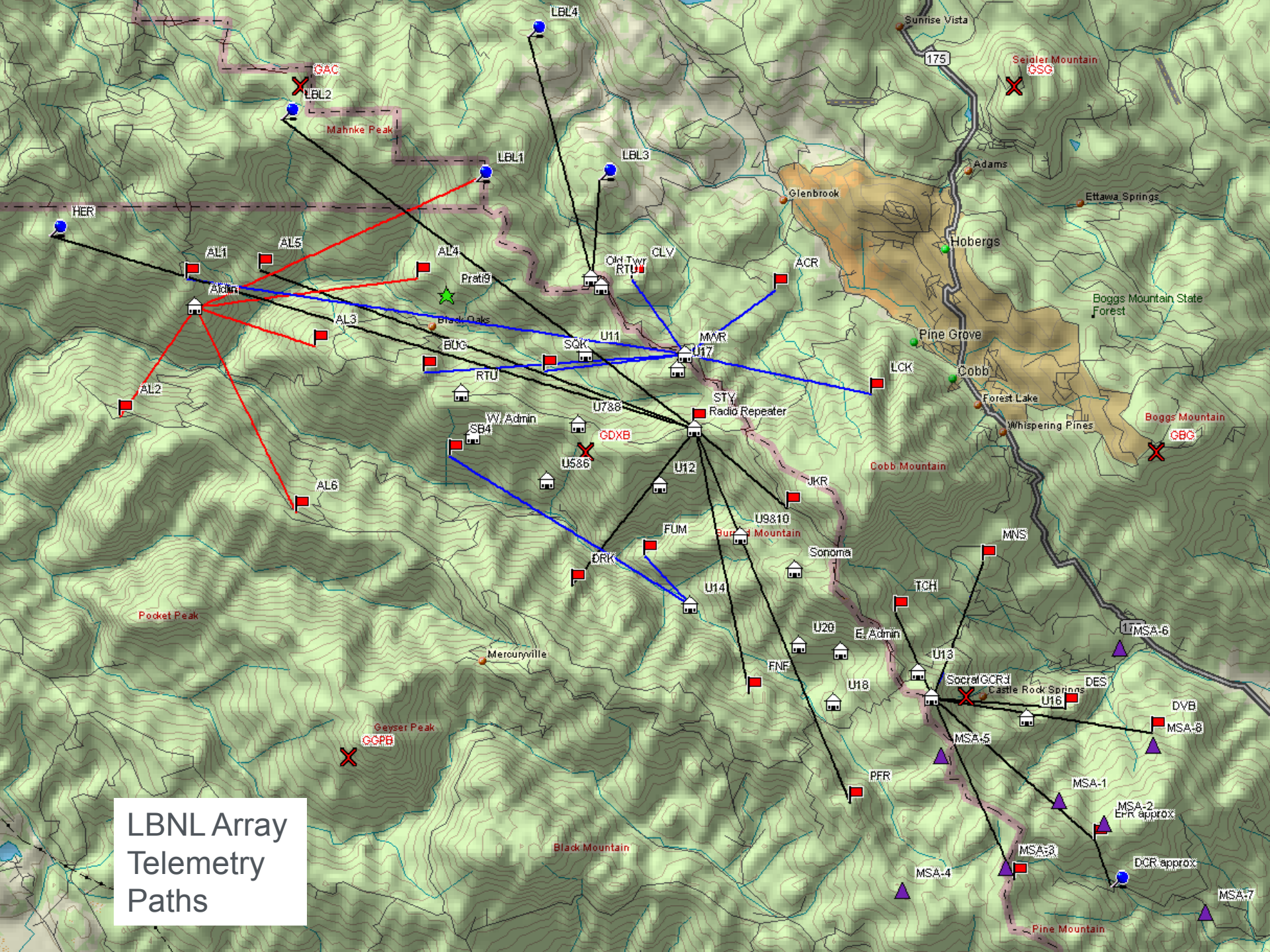
- All stations upgraded with new batteries, new 3-C 4.5 Hz geophones
- Serviced all solar panels, electronics, and misc. electronics.
- Added 6 new stations (5 in NW and 1 in SE)
- Upgraded LAN to allow increased real-time data flow

•Personnel

- Robert Haught (25 years experience in array installations and computational data acquisition)
- John Peterson (25 years in data acquisition and processing)
- Steve Jarpe (20 years experience in data processing, programming and instrumentation development)



MEQ Monitoring Stations
At The Geysers


LBNL Array Telemetry Paths
LBL4
LBL2
GAC
Mahnke Peak
LBL1
LBL3
HER
AL1
AL5
AL4
Admin
Prati9
Old Twr
RTU
CLV
ACR
AL3
Black Oaks
BUC
SQK
U11
MWR
U17
RTU
AL2
STY
Radio Repeater
U7&8
W. Admin
SB4
GDXB
U5&6
U12
AL6
JKR
U9&10
FUM
Burnt Mountain
DRK
U14
Pocket Peak
Mercuryville
U20
E. Admin
FNF
U18
U13
Socral
GCR
Castle Rock Springs
U16
DES
DVB
MSA-8
MSA-5
PFR
MSA-1
MSA-2
EPR approx
MSA-3
DCR approx
MSA-4
MSA-7
Pine Mountain
Black Mountain
Geyser Peak
GGPB
Sonoma
MNS
TCH
MSA-6
Cobb Mountain
LCK
Cobb
Forest Lake
Whispering Pines
Boggs Mountain
GBG
Pine Grove
Boggs Mountain State Forest
Hobergs
Glenbrook
Adams
Ettawa Springs
Sunrise Vista
175
Seigler Mountain
GSG

Task 2 Research on Seismicity and Injection/Production

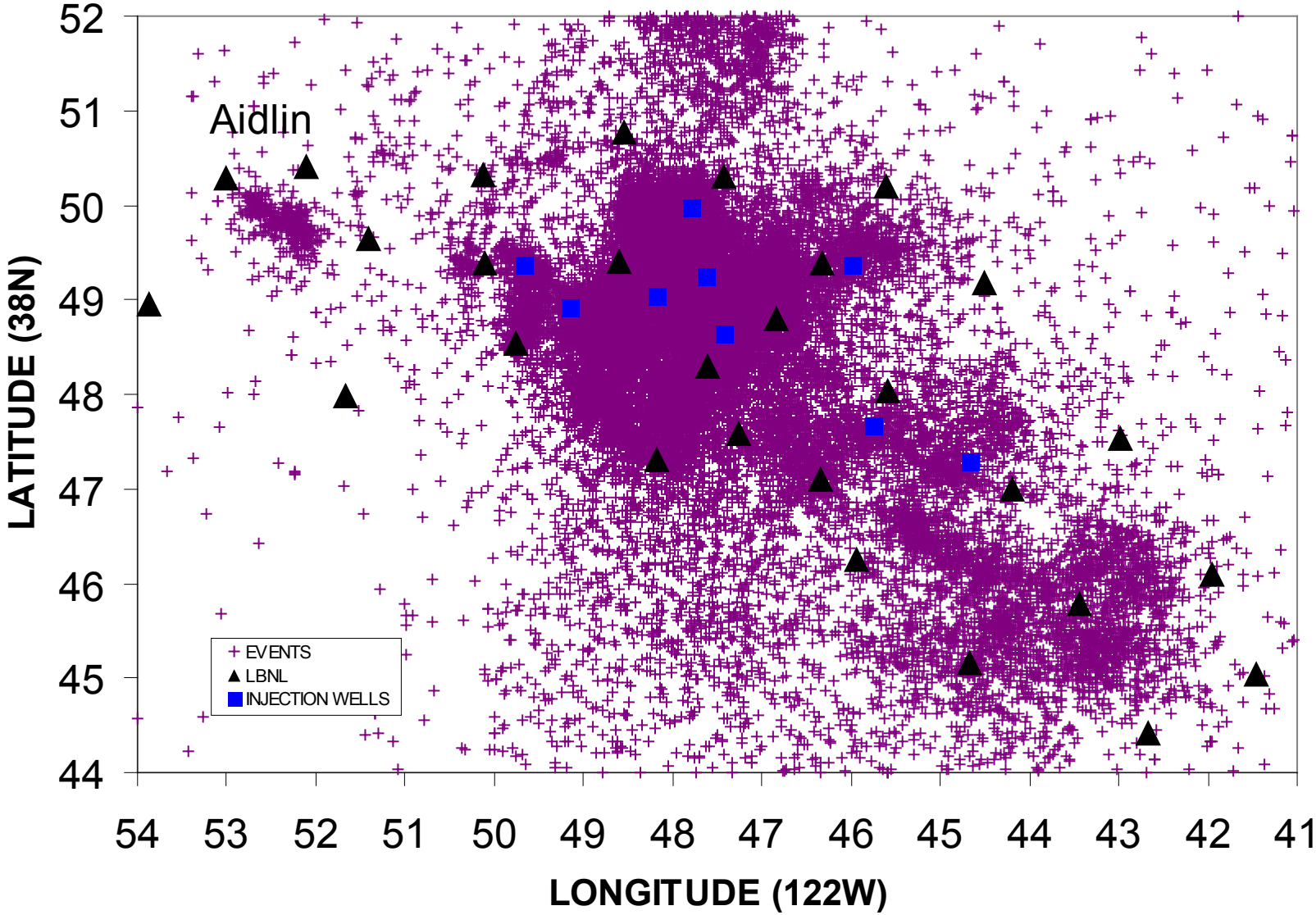
- P and S wave auto picker tested and “tuned” for Geysers area
- 113,000 events relocated
- “Donut hole” verified and redefined.

•Personnel

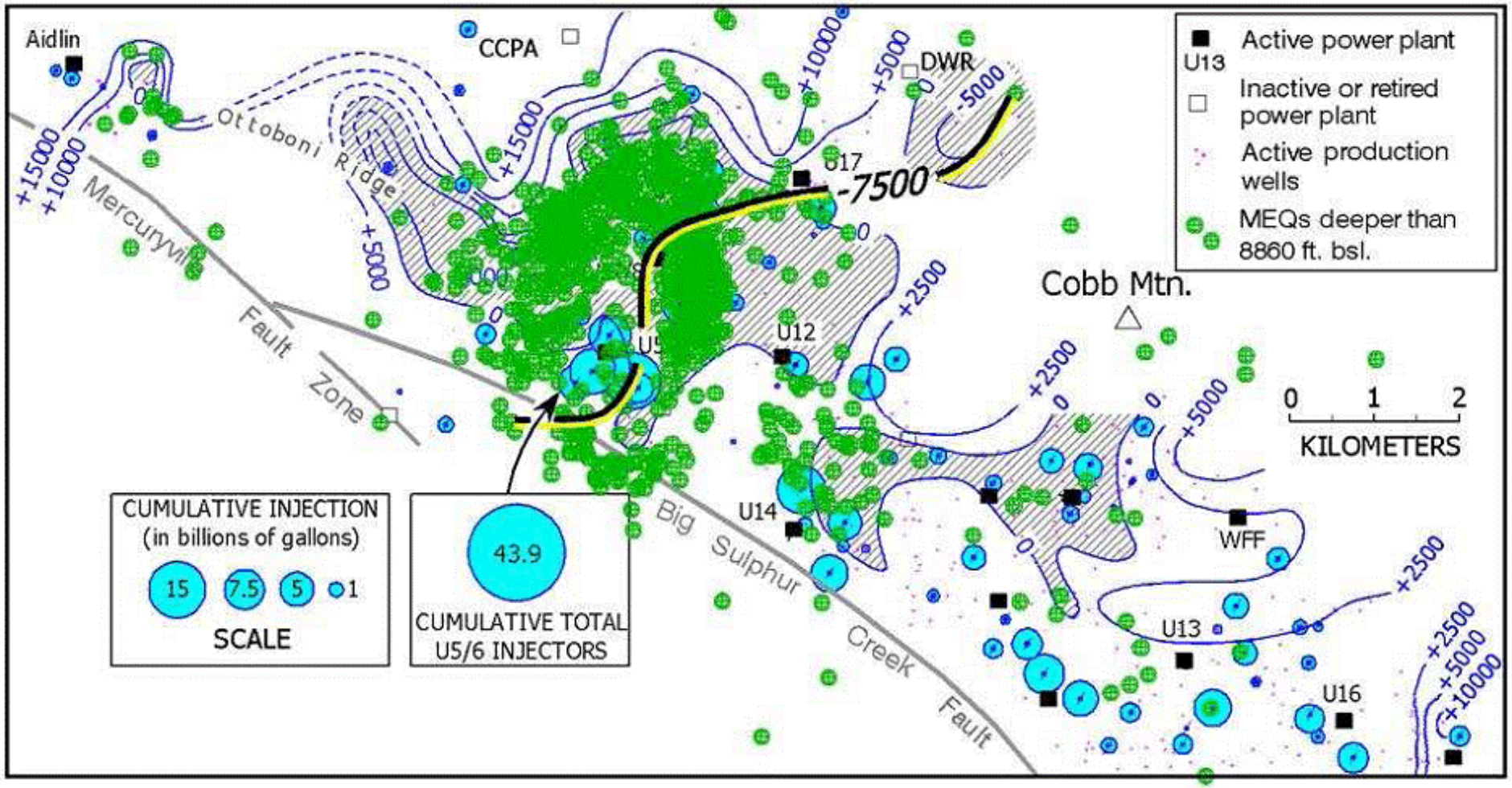
- Steve Jarpe (see above)
- Robert Nadeau (Scientist) Expert in seismicity studies and development of location methods
- Larry Hutchings (Scientist) and Katie Boyle (data analysis) Developed improved auto (P and S wave) pickers, tomographic 3-D analysis, source mechanism studies and location programs.

ALL EVENTS OCT 2005 - SEP 2008

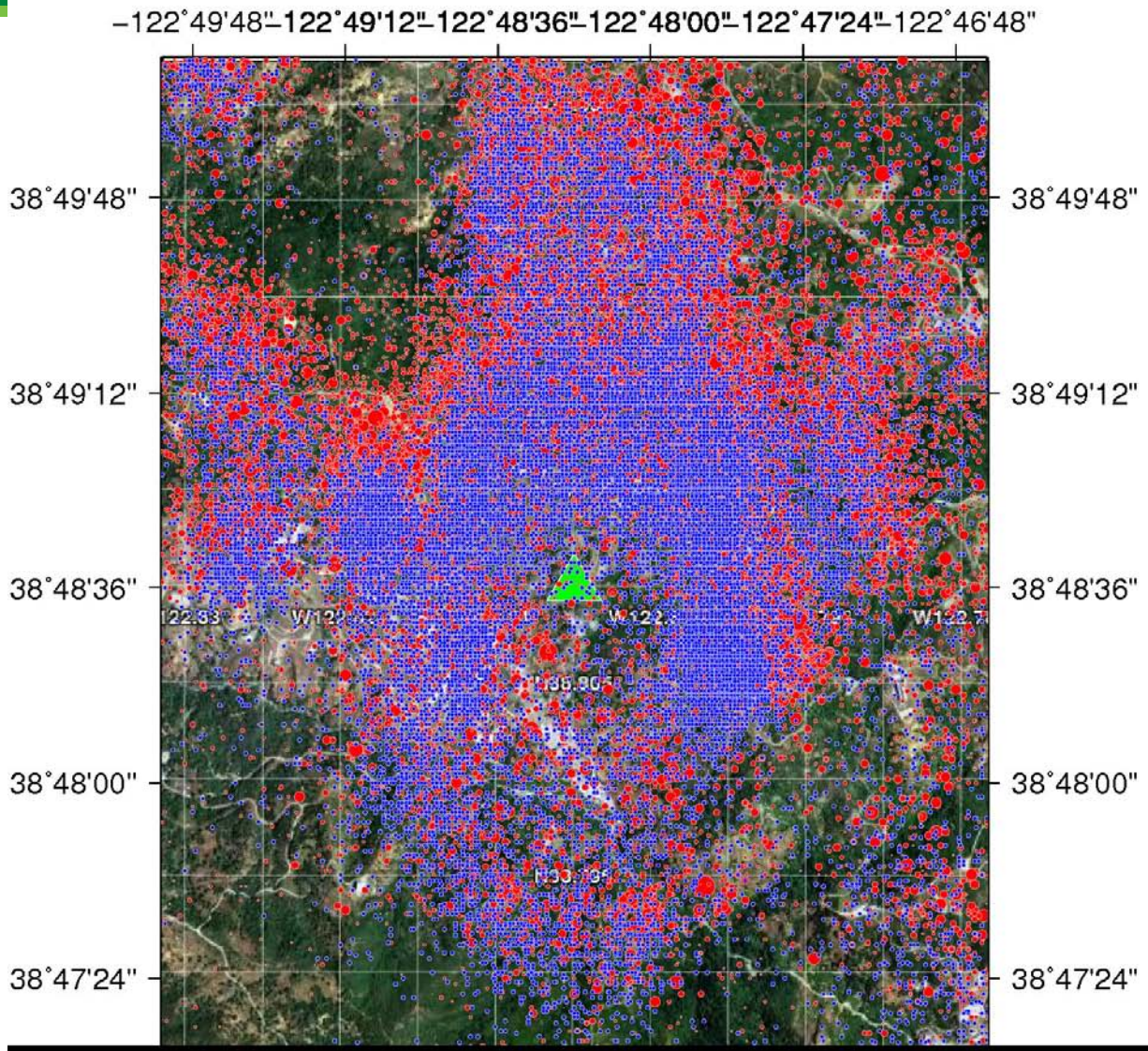
59,980 Events (1020 Mag >2, 58 Mag >3, 4 Mag >4)



The MEQ "doughnut hole" is defined as the MEQ events (green) around a relatively aseismic "hole"



The Geysers


−122°49'48"
−122°49'12"
−122°48'36"
−122°48'00"
−122°47'24"
−122°46'48"
38°49'48"
38°49'12"
38°48'36"
38°48'00"
38°47'24"

Project Management/Coordination

- Project Management
  - PI Ernie Majer (LBNL) Overall responsibility for all aspects of project and Scientific/Technical direction
  - Mark Delinger (Lake County) Project interface with DOE, Funds Manager
  - Mark Walters (Calpine) Industry lead and scientific coordinator
- Schedule
  - Task 1 and 2. Continue in parallel throughout project
- Application of resources and leveraged funds/budget/spend plan
  - Funds will be spent in a linear fashion except in year 1 which will see increased spending in Task 1 for array expansion
  - In years 2-5 approximately $75 K /year will be spent in Task 1 (including cost share by industry)
  - $175K /year Task 2 (including cost share)
- How is this project integrated with other projects in the program?
  - Results will be used for any EGS project at The Geysers and for any project that needs seismicity versus injection /production data
- Coordination with industry & stakeholders
  - Industry and Public rely upon results to continue geothermal energy production at The Geysers

Future Directions

- Deployment strategy, future research, development or deployment needs.
  - MEQ analysis is a critical element in all EGS projects, knowledge transfer will occur through publications, direct data transfers and working directly with industry
- Explain what it is you plan to do during the rest of this year (FY10) and next year (FY11).Highlight upcoming key milestones.
  - See previous slides
- Decision points, remaining issues, alternative pathways.
  - Task 1: Future additional instrumentation may require additional funds, may be forced to operate at reduced capacity due to natural disasters
  - Task 2: Depending on the needs of the operations and development of EGS over the project length the study areas may shift

Summary Slide

- Continued real-time high resolution (independent) comprehensive monitoring of The Geysers is important for:
  - Keeping the public informed and to support EGS development
  - Continuity of data
  - Provide data to all interested parties
- Research is important for:
  - Understanding how to mitigate seismicity
  - Designing efficient and cost effective development of EGS systems
  - Rare opportunity to examine reservoir processes in detail over an extended period