



A GENERATION AHEAD,
today

Seismic Monitoring Advisory Committee Meeting

16 November 2015
Geothermal Visitors Center
Middletown, California

Reporting Period:
01 April 2015 to 30 September 2015



Craig Hartline
Senior Geophysicist
Calpine Corporation

C L E A N M O D E R N E F F I C I E N T F L E X I B L E P O W E R G E N E R A T I O N

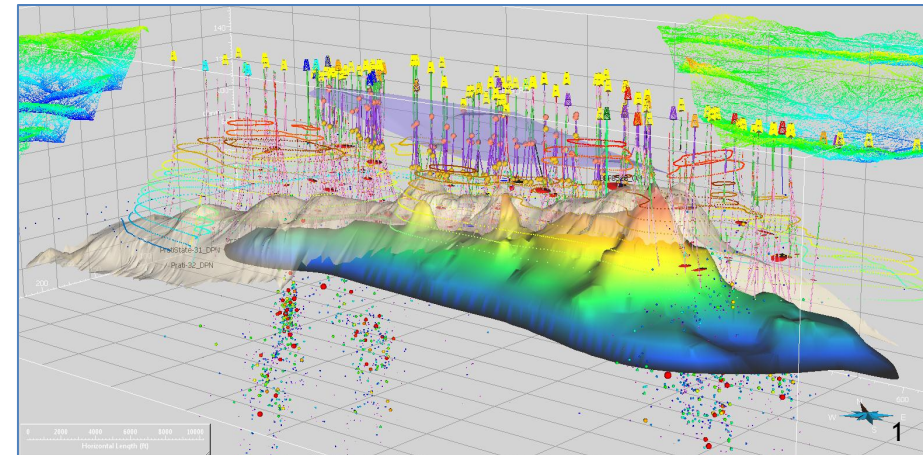
Seismic Monitoring Advisory Committee Meeting

Calpine Presentation Agenda

Reporting Period: 01 April 2015 to 30 September 2015



- Valley Fire Damage and Current Status of Seismic Monitoring Networks
 - LBNL Seismic Monitoring Network
 - USGS / Northern California Seismic Network
 - Strong Motion Stations
- Seismicity Hotline
- Field-wide Seismicity Analysis
- Yearly Field-Wide Water Injection and Seismicity
- Monthly Field-Wide Water Injection and Seismicity
- Daily SRGRP Water Supply
- Strong Motion Sensor Station Analysis
- Seismicity, Fracture Zones and Reservoir Compartmentalization
- 3D Visualization and Structural Model Building
- Additional Seismic Monitoring and Research



Seismic Monitoring Advisory Committee Meeting

LBNL Seismic Monitoring Network

Valley Fire Damage and Repairs



One LBNL station (DES) was totally destroyed by the Valley Fire, and several other LBNL stations sustained varying degrees of damage (MNS, ACR, DEB, ACR, FNF ...) and were quickly repaired by Ramsey Haught.

A *preliminary* estimate of equipment and manpower costs for LBNL Geysers seismic monitoring equipment replacement is in the range of \$10,000 to \$12,000.

Below: LBNL contractor Ramsey Haught and LBNL employee Alex Morales rebuilding LBNL seismic monitoring stations DES and MNS in the southeast Geysers (assisted by Calpine Geophysicist Craig Hartline).

DES: Total Destruction of Solar Panel, Batteries, Electronics, Cables, GPS Unit, RF Antenna and Seismic Sensor



DES: Repairs in Progress. In Photos Are Ramsey Haught (left) and Alex Morales



MNS: Solar Panel and Cables Destroyed, Including ~250' Radio Frequency Cable to Remote Antenna



MNS: Repairs in Progress



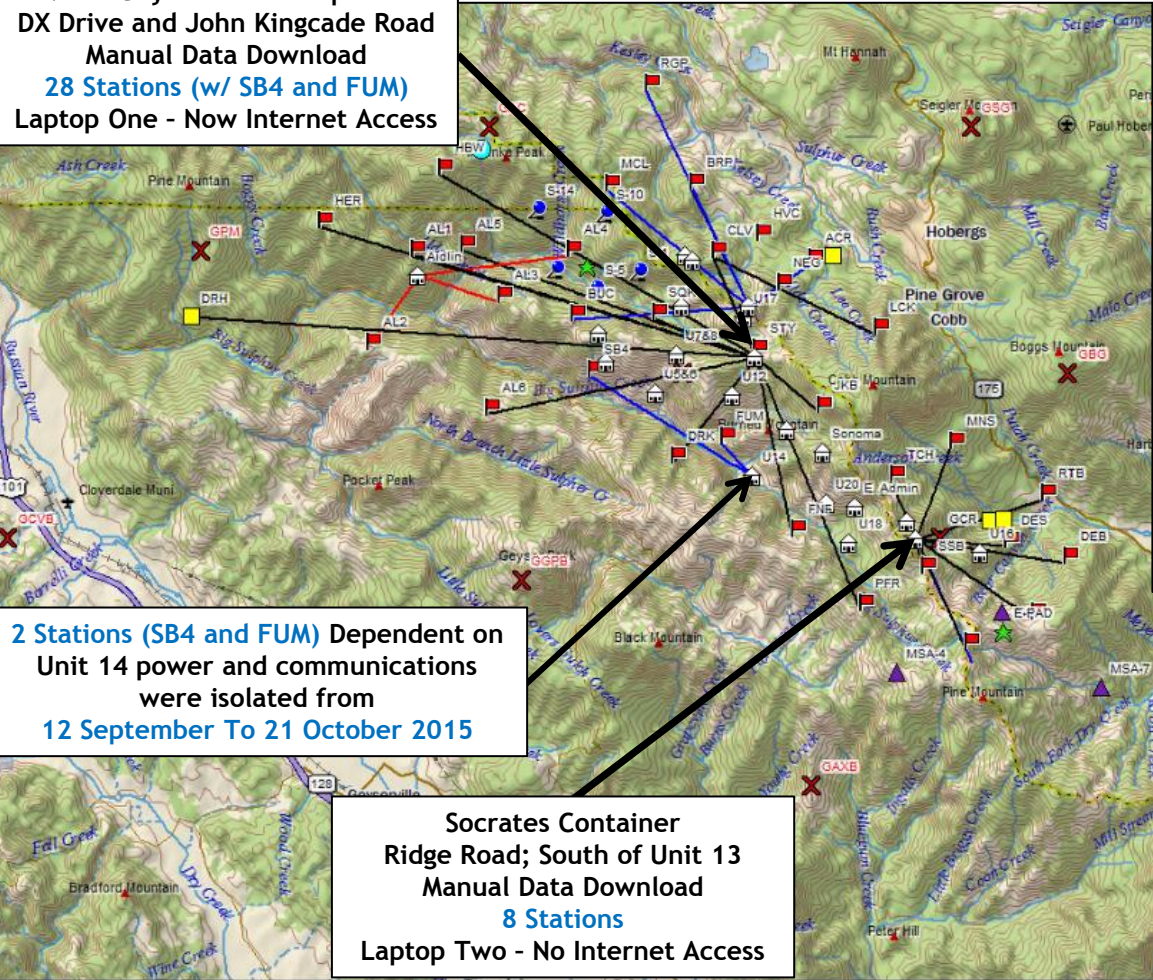
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LBNL Seismic Monitoring Network Status After Valley Fire



LBNL seismic data is sent by radio telemetry to (1) the North Geysers Radio Repeater, and (2) the Socrates Container. The 28 stations received at (1) are now sent via the internet to meq.lbl.gov by the normal file transfer programs. The 8 stations received at (2) will be manually downloaded until restoration of the “Calpine Fiber Loop” communications to the Geysers Administration Center.

North Geysers Radio Repeater
DX Drive and John Kingcade Road
Manual Data Download
28 Stations (w/ SB4 and FUM)
Laptop One - Now Internet Access



- LBNL Permanent Station (3-Component)
- Geothermal Power Plant
- Strong Motion Station
- USGS Permanent Station (3-Component)
- Portable RefTek Stations (Prati Area)
- Former AltaRock MSA 500' Boreholes

2 Stations (SB4 and FUM) Dependent on Unit 14 power and communications were isolated from 12 September To 21 October 2015

Socrates Container
Ridge Road; South of Unit 13
Manual Data Download
8 Stations
Laptop Two - No Internet Access

Underlying Map Provided by LBNL Contractor Ramsey Haught



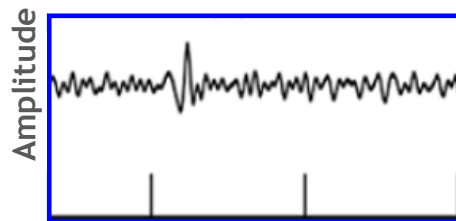
Collaboration with Lawrence Berkeley National Laboratory.

Three-component borehole seismic monitoring stations installed by LBNL contractor Ramsey Haight at:

- | | |
|------------------------------------|-------------------------|
| ➡ (PSB P-Site Borehole) | MSA-2 475' depth |
| ➡ (SRB Sheepskin Ridge Borehole) | MSA-3 457' depth |
| ➡ (SSB Super Sump Borehole) | MSA-5 367' depth; |
| ➡ (RTB Reynolds Trucking Borehole) | MSA-6 454' depth |
| ➡ (DEB Davies Estate Borehole) | MSA-8 490' depth |

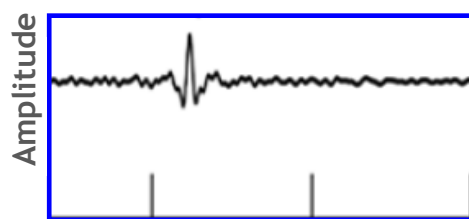
22 July 2015 Installation

Surface Sensor - More noise

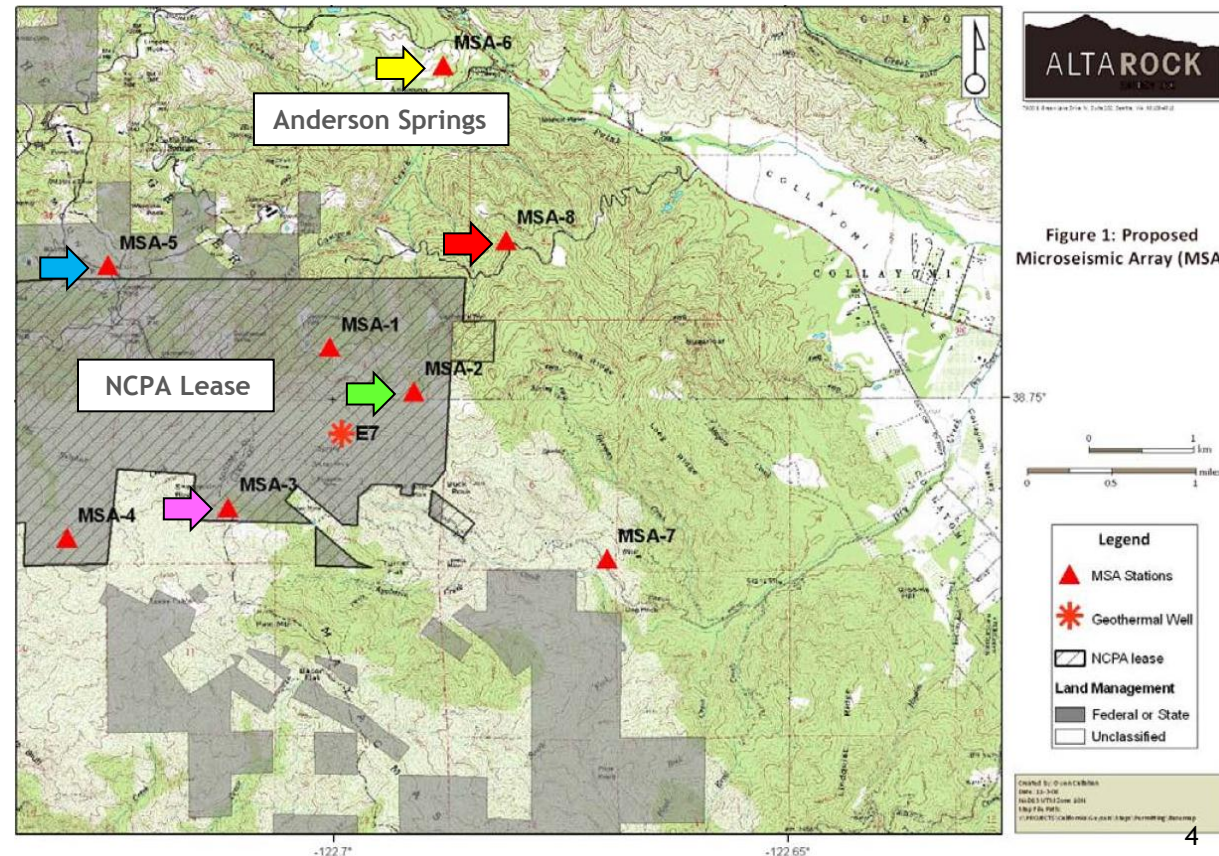


Time

Borehole Sensor - Less noise



Time



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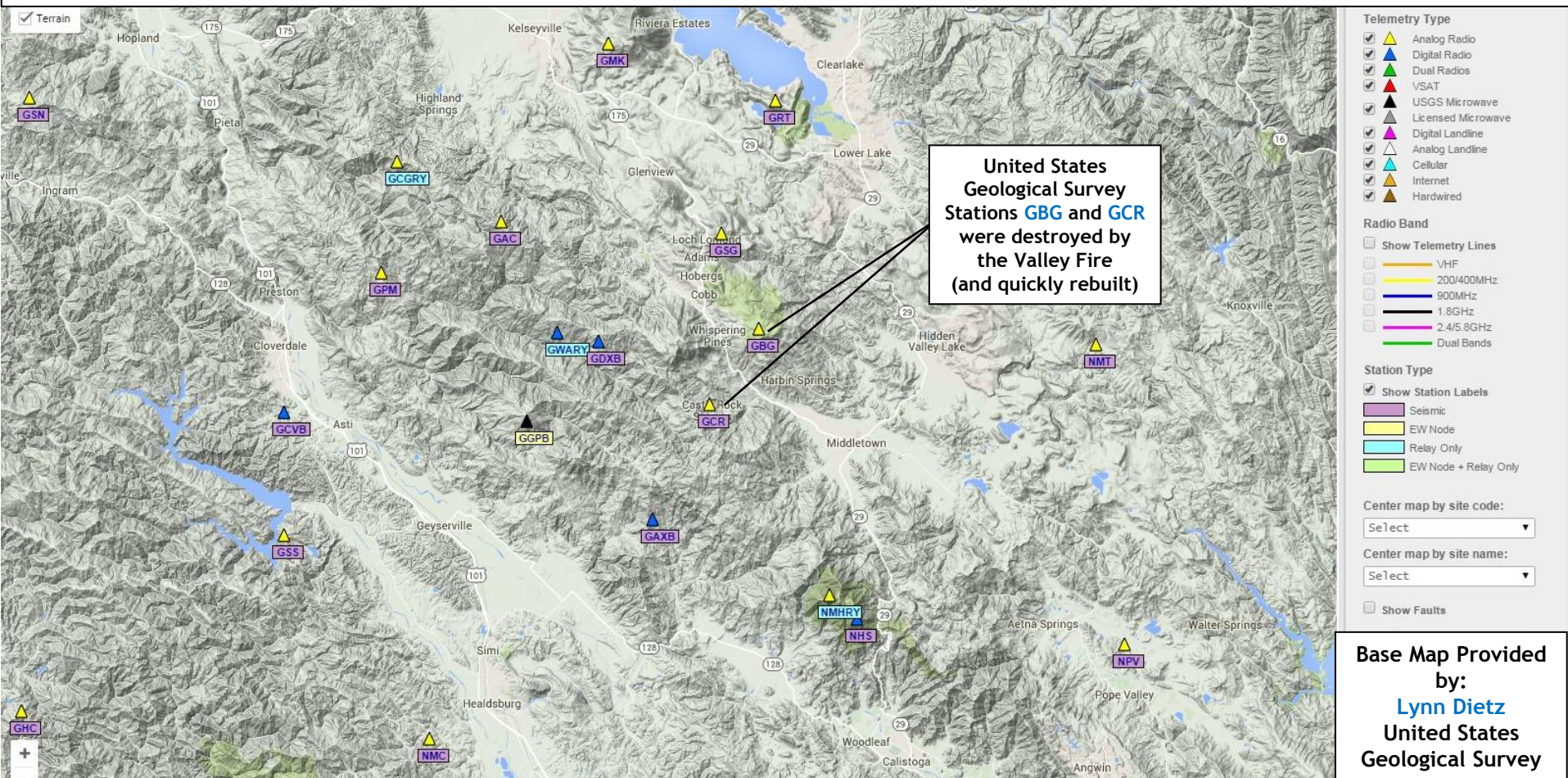
USGS / Northern California Seismic Network

Seismic Sensor Stations and Communication Links



Two **United States Geological Survey** (USGS) seismic monitoring stations destroyed by the Valley Fire were quickly repaired. The **USGS Waveserver** in Geysers Administration Room 278 was no longer functional, likely due to a fire-related power spike. A replacement USGS Waveserver server was constructed by the USGS and installed by LBNL contractor Ramsey Haught.

The **Northern California Seismic Network** provides *real-time* seismic data for The Geysers. The real-time data resolution was slightly degraded until the sparse **regional USGS seismic network** data and the dense **Geysers LBNL seismic network** data could once again be merged prior to automated event processing. This required the repair of several communications links, including the 05 November 2015 restoration of the microearthquake virtual local area network (MEQ VLAN).



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Kinematics ETNA Strong Motion Stations

Valley Fire Damage and Equipment Replacement



- COB** reported as destroyed by USGS (confirmation requested).
- ADSP** housing fire-damaged; no power or communication.
- ADS2** locked within snack bar at community center. may have have survived; no power or communication.

Working with LBNL on solution for “next-generation” strong motion instruments.

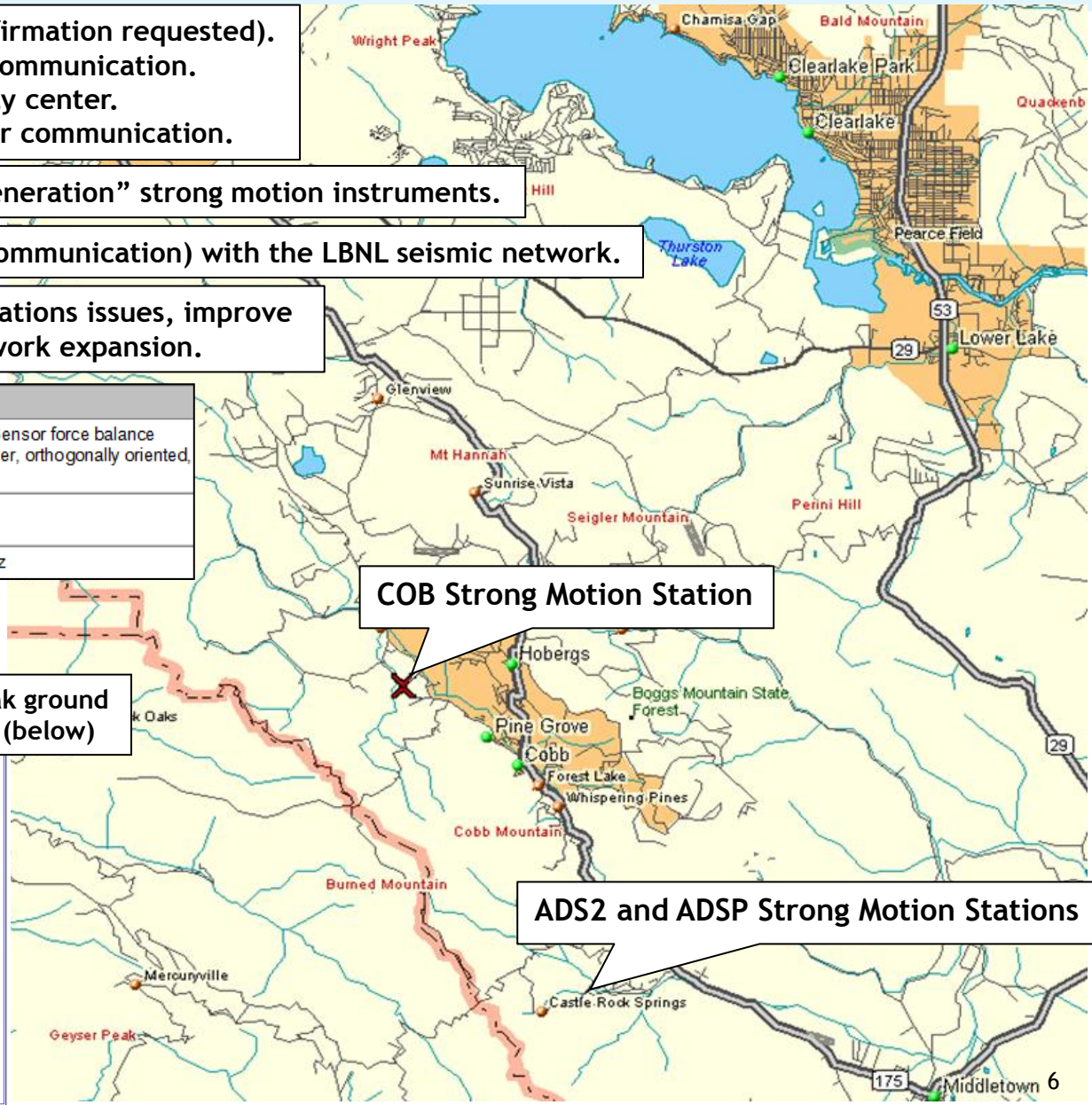
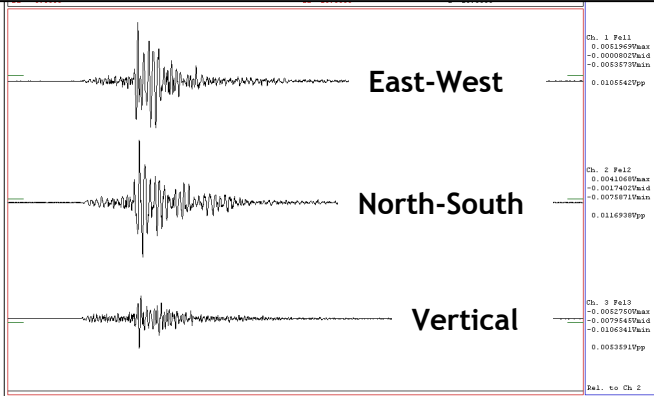
Suggest solar power and radio telemetry (communication) with the LBNL seismic network.

Goals: Minimize rural power and communications issues, improve network reliability, allow potential for network expansion.



Sensor	
Type:	Triaxial EpiSensor force balance accelerometer, orthogonally oriented, internal
Full scale range:	2g
Bandwidth:	DC to 200 Hz

ETNA system installed in 2003 (above) and peak ground acceleration for three components of motion (below)



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Santa Rosa Geysers Recharge Project

Environmental Impact Report Mitigation Measures

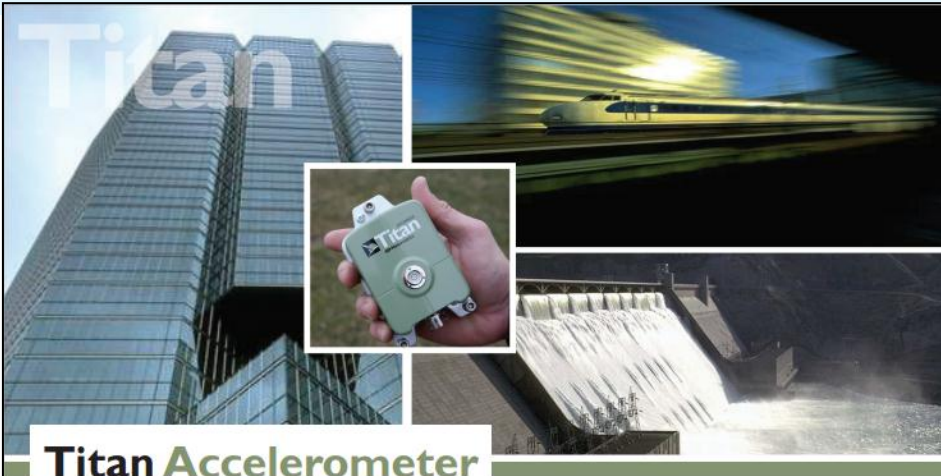
The Environmental Impact Report (EIR) for the Santa Rosa Geysers Recharge Project (SRGRP) addresses the possibility of induced seismicity associated with the increased injection (Greensfelder and Parsons, 1996). The EIR (page 2-119) specifies a number of mitigation measures to be implemented as the SRGRP becomes operational. The mitigation measures, and how they are fulfilled, are specified below:

Mitigation Measure	How it is addressed
"... the local seismographic station network maintained by the Geysers operators ... shall be upgraded to focus coverage around the wells proposed for injection."	New digital array funded by California Energy Commission (Lawrence Berkeley Lab <i>et al.</i> , 2004). Four new LBNL stations added in the northwest Geysers in January 2010. Two new LBNL stations added to the northeast Geysers in March 2011 (31 total).
"Accelerograph stations shall be added in Cobb and Anderson Springs to allow operators to determine relationships between seismic events within the Geysers steamfield and felt effects in nearby communities."	Data (Appendix 1) and results from the strong-motion accelerograph stations installed in March 2003 at Cobb and Anderson Springs.
"Software shall be improved to enable routine automated locating and mapping of epicenters ... and analysis of data"	Upgraded processing and picking procedures associated with new array funded by California Energy Commission (Lawrence Berkeley Lab <i>et al.</i> , 2004).

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Strong Motion Stations

Potential Replacement Equipment - Nanometrics Titan Accelerometer



Titan Accelerometer

The Titan is a force balance triaxial accelerometer that provides exceptional performance over a wide frequency range from DC to 430 Hz. The Titan features industry leading dynamic range and ultra-low self-noise performance that is comparable to that of some broadband seismometers. Combine the Titan with the Centaur digitizer to achieve a complete data acquisition and recording system that is suitable for deployment in both remote and networked locations.

The Titan is the first accelerometer to incorporate digitally selectable full scale range and offset zeroing capabilities; features that are ideal for difficult to access or remote deployments, where site visits should be minimized.

The triaxial sensor and electronics are housed in a rugged, compact aluminum enclosure featuring a single bolt anchoring slot, adjustable leveling screws and integrated bubble level.

The Titan Accelerometer has been designed to provide the highest performance available while ensuring efficient, low cost deployments and ease of use.

Industry Leading Performance Attributes:

- Industry leading 166 dB dynamic range
- Ultra-low self-noise comparable to some broadband seismometers
- Wide operational frequency range: DC to 430 Hz
- Best in class thermal stability and high accuracy provide increased data quality
- Full scale range of ± 0.25 g to ± 4 g with independent horizontal and vertical range selection

Ease of use advantages:

- Electronically selectable full scale range facilitates remote sensor control when deployments are distant or difficult to access
- Integrated web server provides efficient instrument management and control
- Installation features that include an integrated bubble level, adjustable leveling screws, single bolt keyhole mount, and a compact footprint ensure that deployments are completed efficiently and quickly



Titan accelerometer connected to and powered by a Centaur Digitizer

Specifications

Accelerometer Technology and Performance	
Topology	Triaxial, horizontal-vertical
Feedback	Force balance with capacitive displacement transducer
Centring	Electronic offset zeroing via user interface or control line
Full-scale Range	Electronically selectable range: ± 4 g, ± 2 g, ± 1 g, ± 0.5 g, and ± 0.25 g (peak)
Bandwidth	DC to 430 Hz (-3 dB point)
Dynamic Range (Integrated RMS)	166 dB @ 1 Hz over 1 Hz bandwidth 155 dB, 3 to 30 Hz
Offset	Electronically zeroed to within ± 0.005 g
Non-linearity	$< 0.015\%$ total non-linearity
Hysteresis	$< 0.005\%$ of full scale
Cross-axis Sensitivity	$< 0.5\%$ total
Offset Temperature Coefficient	Horizontal sensor: $60 \mu\text{g}/^\circ\text{C}$, typical Vertical sensor: $320 \mu\text{g}/^\circ\text{C}$, typical

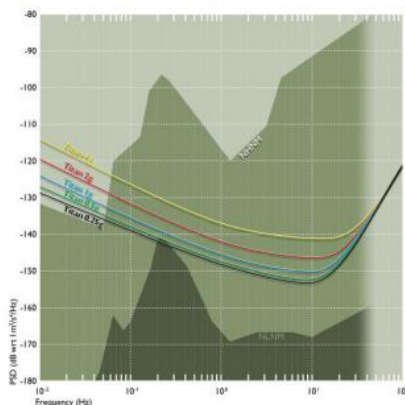
Digital Command and Control Interface	
Digital Interface	Onboard web server standard HTTP RS-232 compatible Serial Line Internet Protocol (SLIP) RS-232 command-line interface
Commands	Gain range selection Auto-zero, or set to specific offset Self-test Calibration enable State of health request Firmware updates
Data Outputs	Sampled XYT outputs (in volts and g) Instrument temperature Trimmer settings Instrument serial number Hardware assemblies and firmware revisions

Physical and Environmental	
Housing	Aluminum, surface resistant to corrosion, scratches, and chips
Mounting	Single bolt keyhole mount
Leveling	Integrated bubble level Adjustable locking levelling screws
Size	Length: 14 cm (5.5") Width: 8.5 cm (3.3") Height: 5.8 cm (2.3")
Weight	960 g (2.1 lb)
Operating Temperature	-40°C to 60°C
Storage Temperature	-65°C to 75°C
Humidity	0 to 100%
Weather Resistance	Rated to IP-67

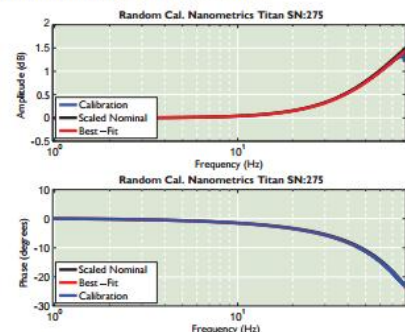
Hardware Interface	
Connectors	MIL-C-26482G Series 1, 14-pin, shell size 12
Acceleration Output	40 Vpp differential
Output Impedance	$2 \times 100 \Omega$
Calibration Input	Single voltage input, all channels enabled together
Control Input	Single control signal can be configured to initiate auto-zero, initiate self-test, or enable calibration
Status Output	Asserted: Unit OK, output signal valid Deasserted: Self-test in progress or failed, auto-zeroing in progress, calibration enabled, or starting up
Serial Port	9600 Baud RS-232 compatible

Power	
Supply Voltage	9 to 36 V DC isolated input
Power Consumption	1.1 W typical quiescent
Protection	Reverse-voltage and over-/under-voltage protected Self-resetting over-current protection
Isolation	Supply power is isolated from signal ground
Grounding	Predrilled holes (4) for M4 x 5 grounding lug screw
Voltage Disconnect	Software configurable (low/high)

Titan Accelerometer Self-Noise



Sensor Performance: Flat Response



Test results courtesy of USGS

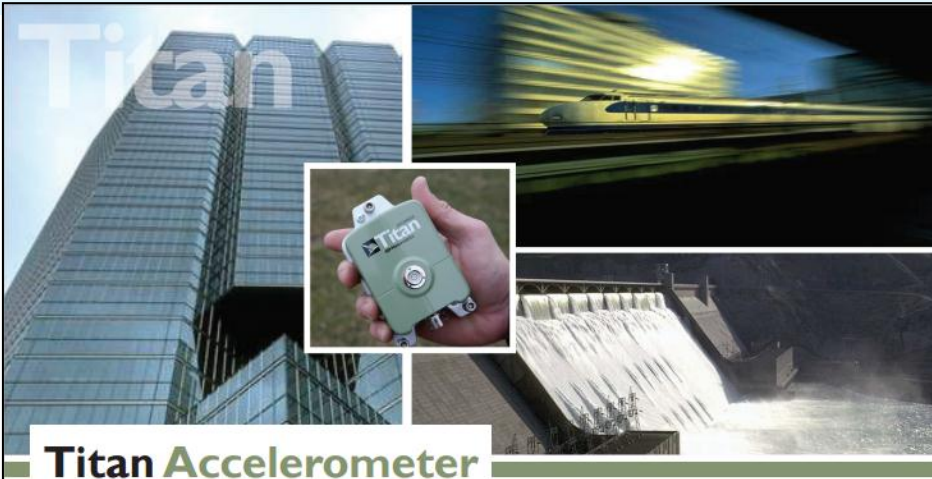
Nanometrics

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Strong Motion Stations

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Titan accelerometer connected to and powered by a Centaur Digitizer

Preliminary Costs for a New Strong Motion Station

\$6200	Nanometrics Taurus Digital Seismograph 24 bit ADC; precision GPS; 138 dB dynamic range, 750 mW
\$4200	Nanometrics Titan Accelerometer DC to 430 Hz; 166 dB dynamic range; +/- 0.25 to 4.0 g
\$3100	Line-of-Sight Radio Telemetry and GPS
\$ 400	One-time Nanometrics License Fee (per unit)
\$ 400	Batteries (2)
\$ 300	Solar Panel
\$ 300	Electronics Container (Hoffman Box)
\$3100	Installation Manpower (24 hours)

\$18,000 Total (+/- 10 percent)









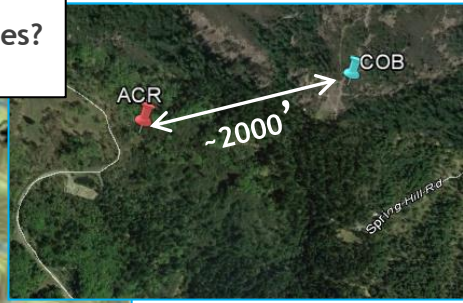
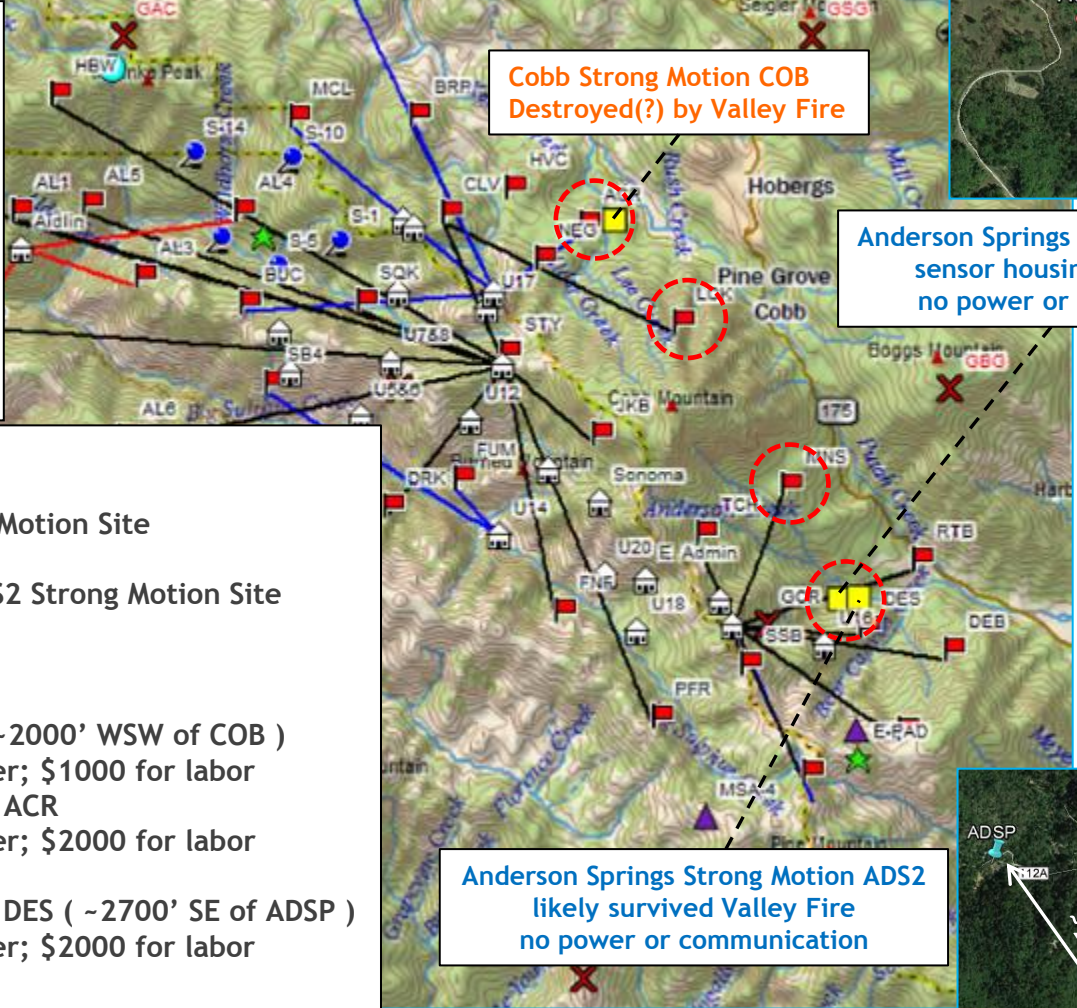
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Strong Motion Stations

Replacement Options and Considerations



Items to Consider:
 Will Cobb and Anderson Springs strong stations be optimally located after resettlement into communities?
 Is strong motion instrument replacement in exactly the same location critical?

-  LBNL Permanent Station (3-Component)
-  Geothermal Power Plant
-  Strong Motion Station
-  USGS Permanent Station (3-Component)
-  Portable RefTek Stations (Prati Area)
-  Former AltaRock MSA 500' Boreholes





Anderson Springs Strong Motion ADSP sensor housing fire-damaged no power or communication

System Replacement

-  Cobb
 - \$18,000 at existing COB Strong Motion Site
-  Anderson Springs
 - \$18,000 at existing ADSP or ADS2 Strong Motion Site

System Conversion

-  Cobb
 - Use of existing LBNL site ACR (~2000' WSW of COB)
 - \$5200: \$4200 for accelerometer; \$1000 for labor
 - Relocation of existing LBNL site ACR
 - \$6200: \$4200 for accelerometer; \$2000 for labor
-  Anderson Springs
 - Relocation of existing LBNL site DES (~2700' SE of ADSP)
 - \$6200: \$4200 for accelerometer; \$2000 for labor

Eventual System Expansion

- Relocation of sites LCK or MNS closer to communities
 - \$6200 per station \$4200 accelerometer; \$2000 labor



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01 April 2015 to 30 September 2015
Seismicity Hotline 1-877-4GEYSER (Toll Free)



Calls transcribed and reviewed daily.

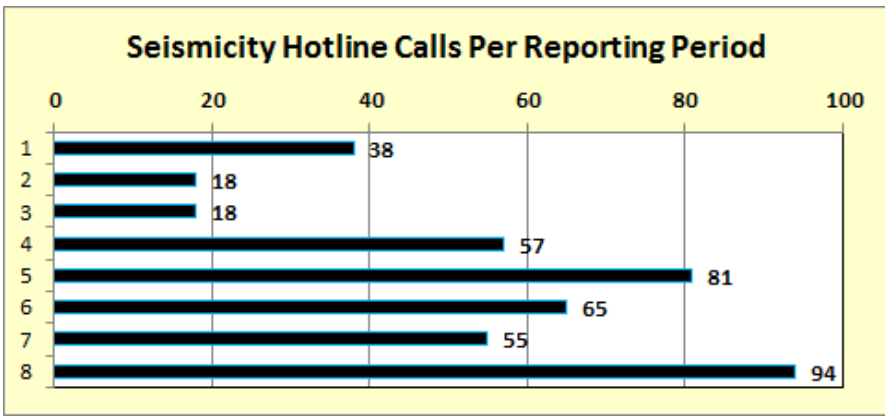
Current Reporting Period

38 calls 01 April 2015 to 30 September 2015

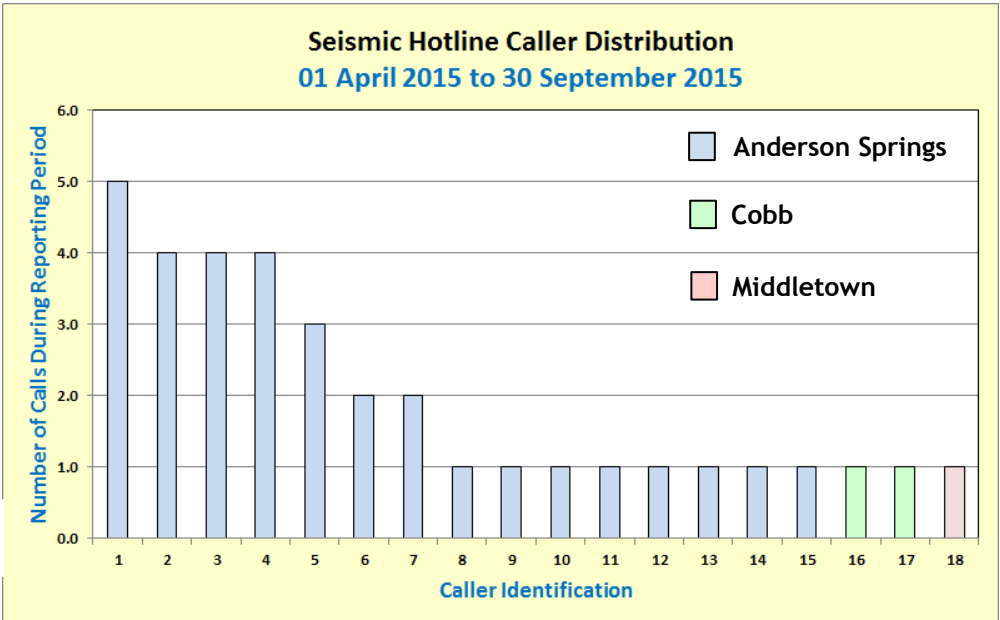
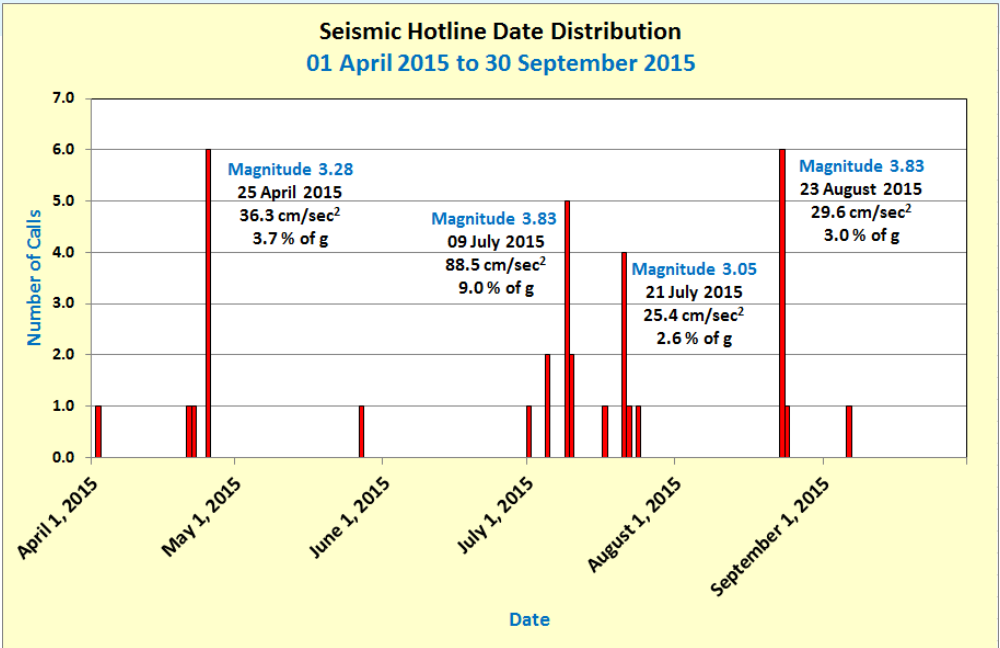
Previous Reporting Periods

- 18 calls 01 October 2014 to 31 March 2015
- 18 calls 01 April 2014 to 30 September 2014
- 57 calls 01 October 2013 to 31 March 2014
- 81 calls 01 April 2013 to 30 September 2013
- 65 calls 01 October 2012 to 31 March 2013
- 55 calls 01 April 2012 to 30 September 2012
- 94 calls 01 October 2011 to 31 March 2012

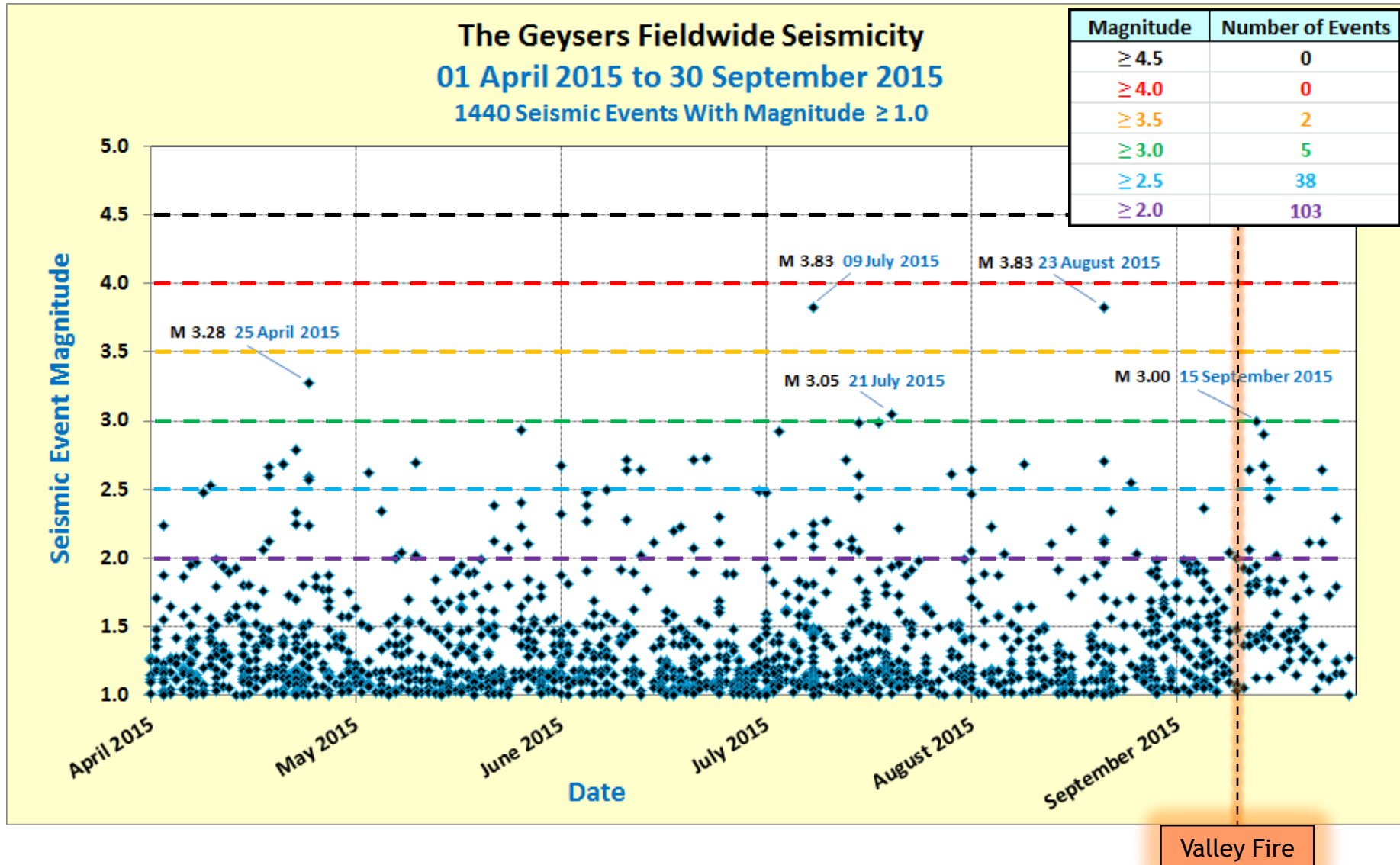
Most Recent Analysis Period at Top of Graph:



There have been no calls to the Seismicity Hotline since 06 September 2015 due to the catastrophic Valley Fire.



Seismic Monitoring Advisory Committee Meeting
Field-wide Seismicity Analysis
01 April 2015 to 30 September 2015 (Current Reporting Period)

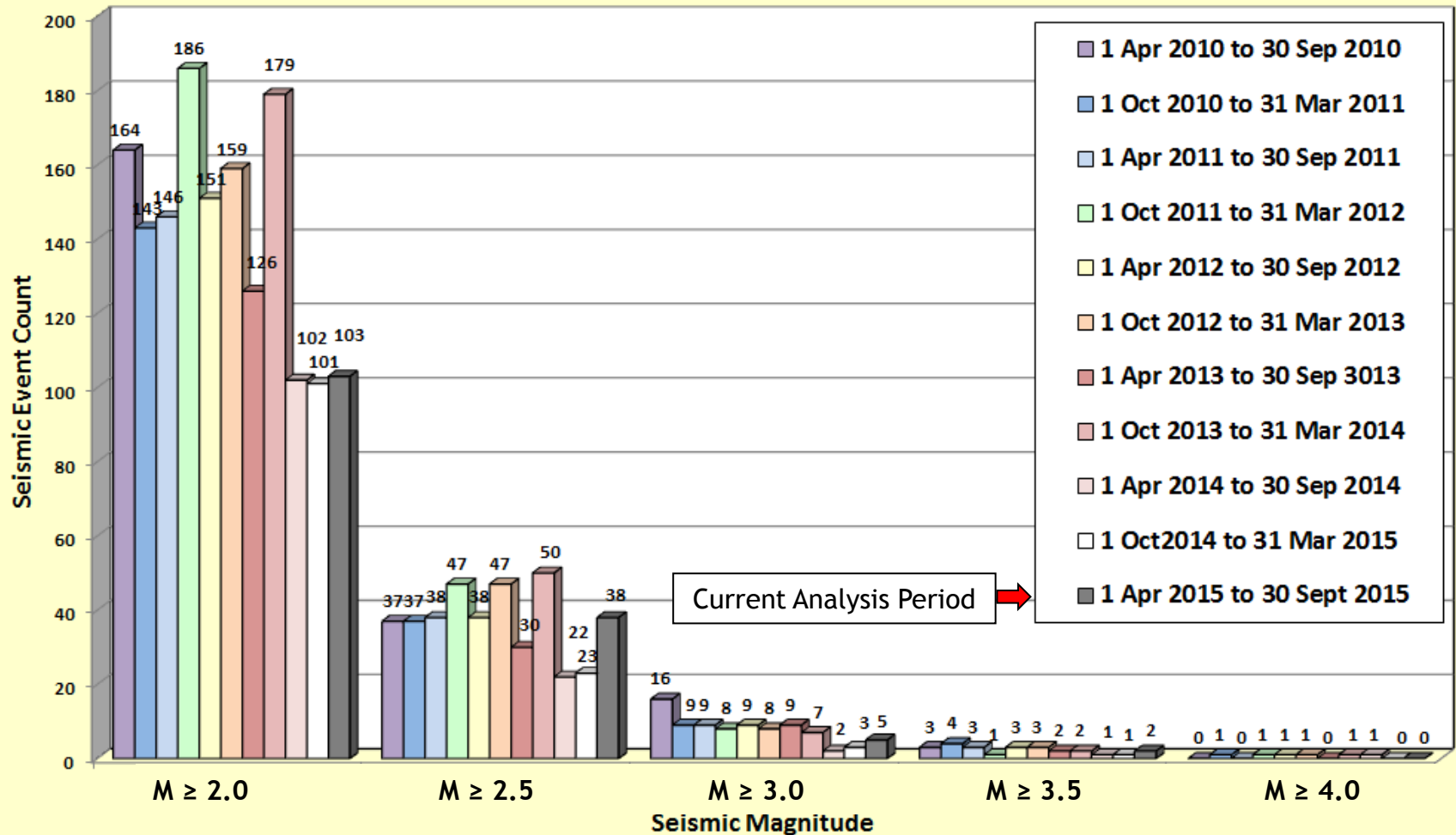


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Field-wide Seismicity Analysis

Comparison of Eleven Semi-annual Reporting Periods

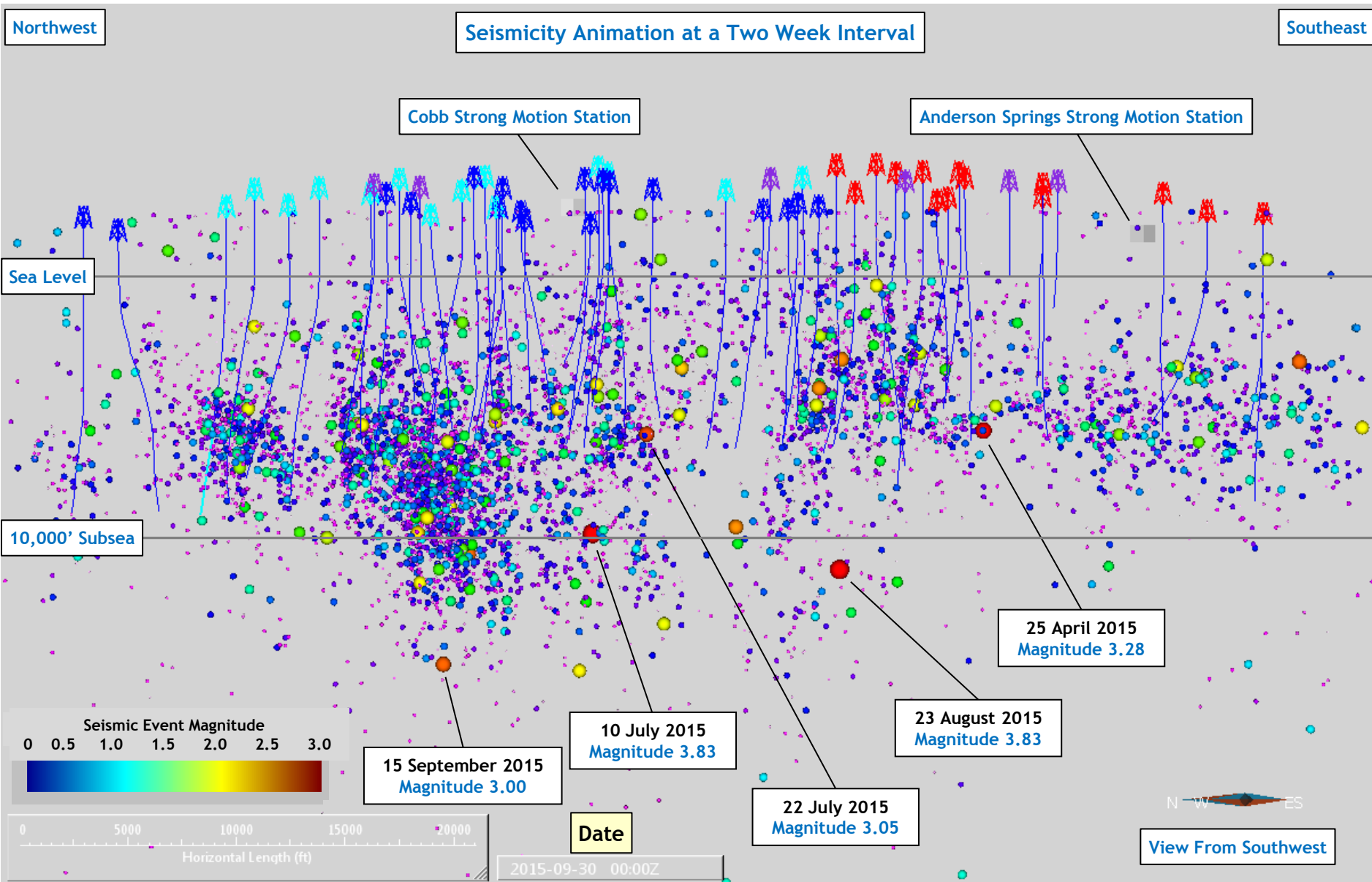
Field-wide Seismicity Analysis
Events \geq Magnitude (X)
Eleven Semi-Annual Periods Since 01 April 2010



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Field-wide Seismicity Analysis

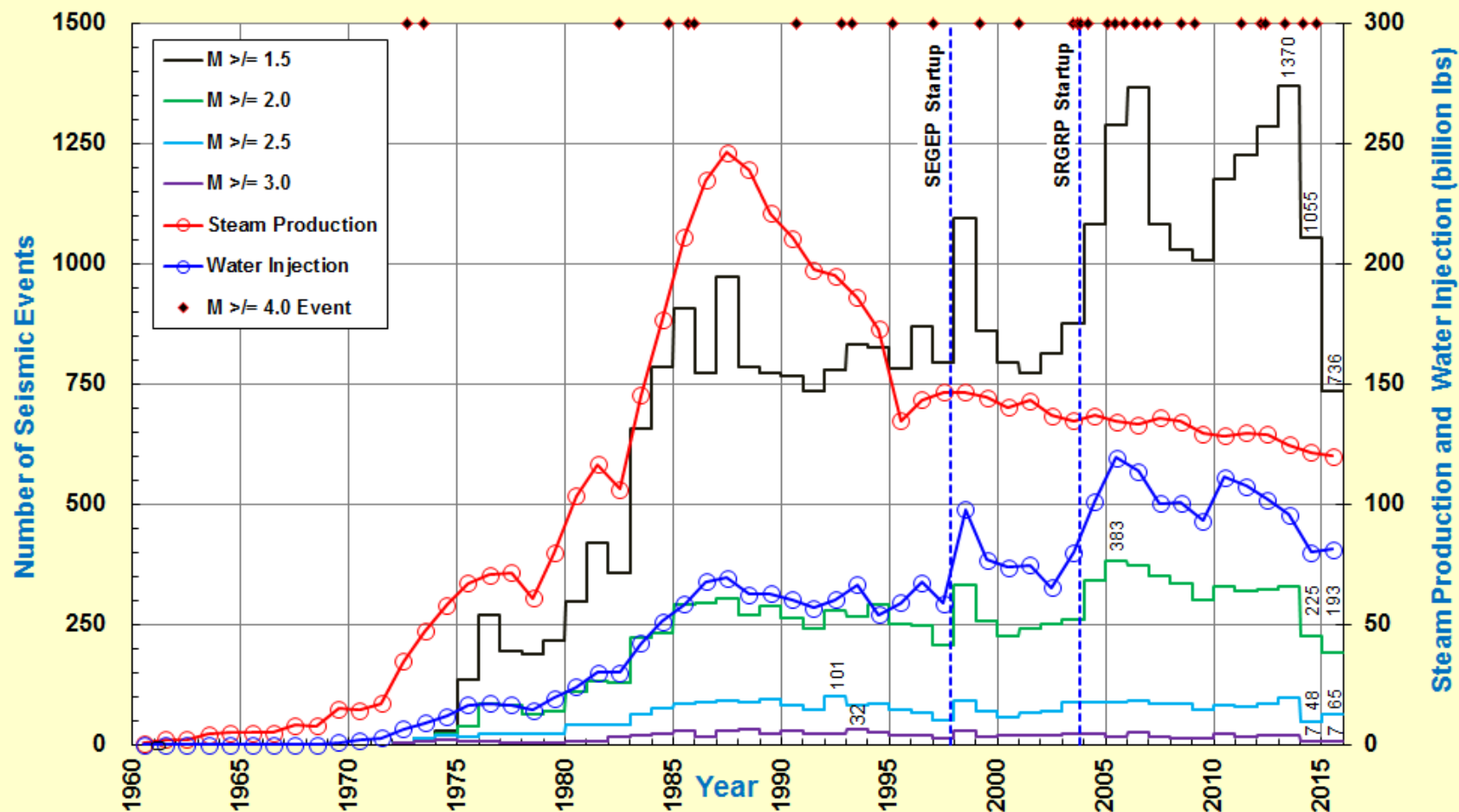
01 April 2015 to 30 September 2015



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Yearly Field-wide Steam Production, Water Injection and Seismicity 1960 Through End 2015 - Projected

The Geysers: Field-wide Steam Production, Water Injection and Seismicity 1960 through end 2015 *



* Seismic event counts projected for final 113 days of 2015 (since Valley Fire on September 12, 2015)

Water injection and steam production values projected for final four months of 2015 (Since 01 September 2015)

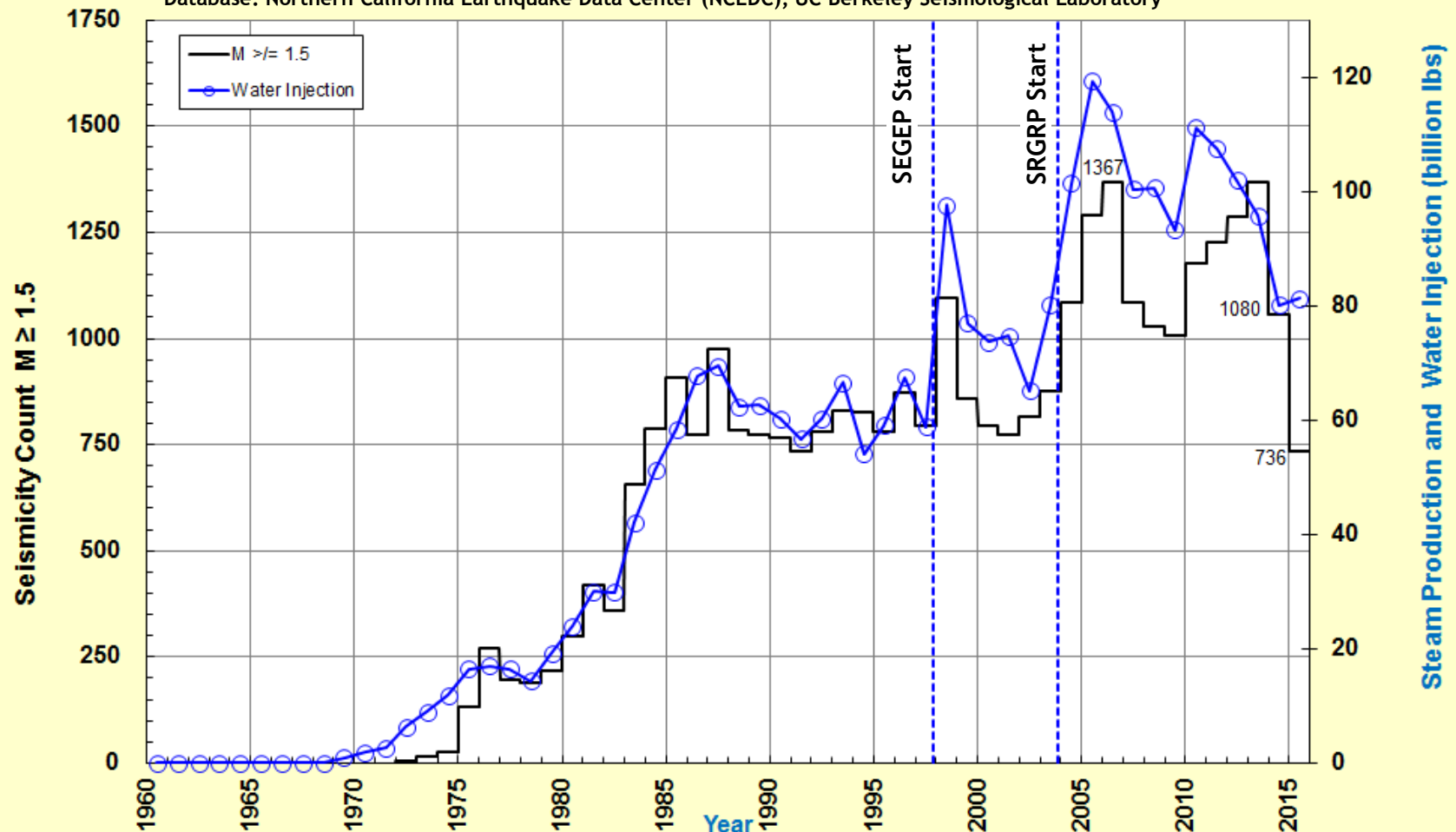
Seismic Monitoring Advisory Committee Meeting

Yearly Field-wide Water Injection and $M \geq 1.5$ Seismicity

1960 Through End 2015 - Projected

The Geysers: Field-wide Water Injection and $M \geq 1.5$ Seismicity 1960 through end 2015 *

Database: Northern California Earthquake Data Center (NCEDC); UC Berkeley Seismological Laboratory



* Seismic event counts projected for final 113 days of 2015 (since Valley Fire on September 12, 2015)
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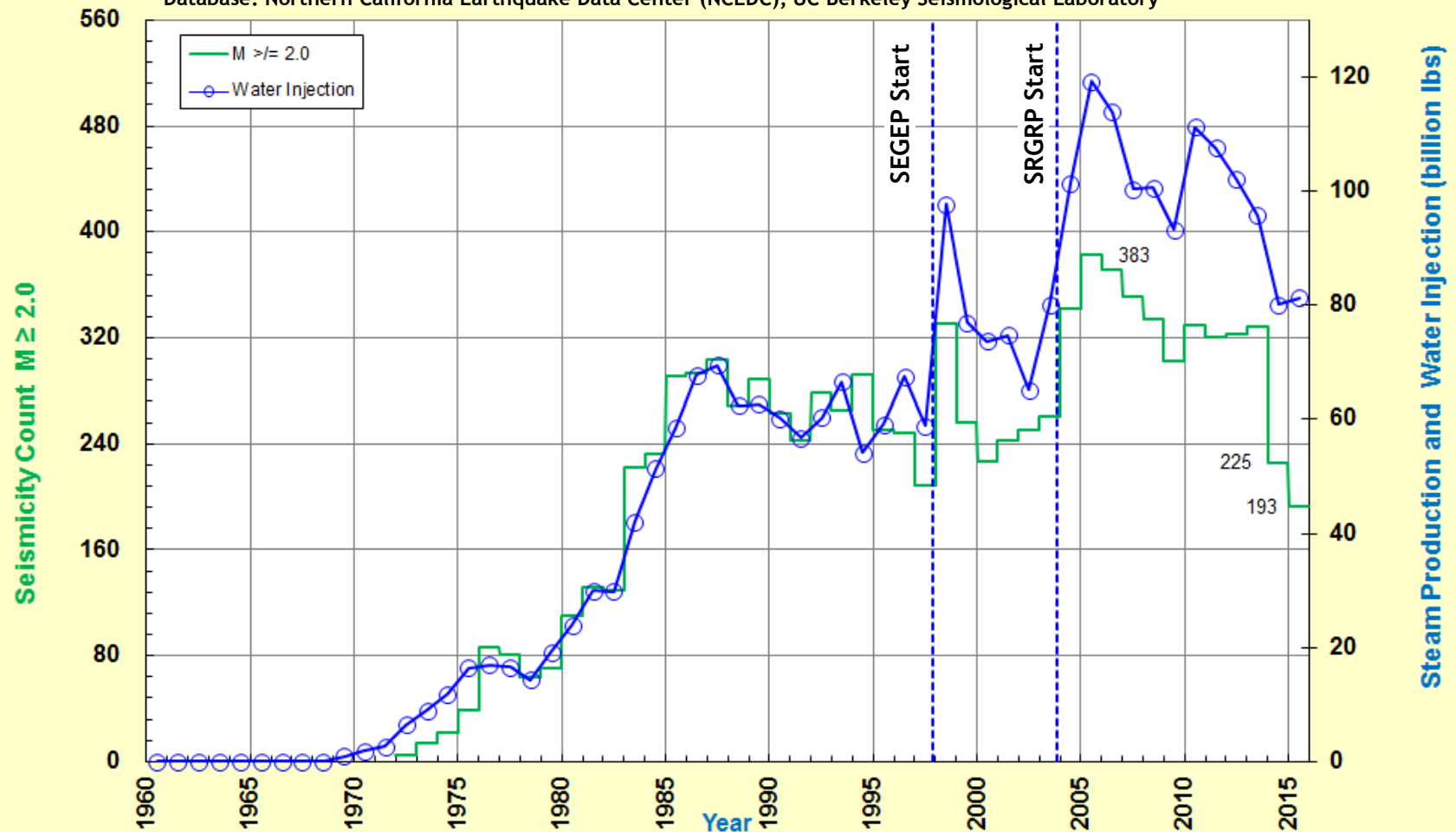
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Yearly Field-wide Water Injection and $M \geq 2.0$ Seismicity

1960 Through End 2015 - Projected

The Geysers: Field-wide Water Injection and $M \geq 2.0$ Seismicity 1960 through end 2015 *

Database: Northern California Earthquake Data Center (NCEDC); UC Berkeley Seismological Laboratory



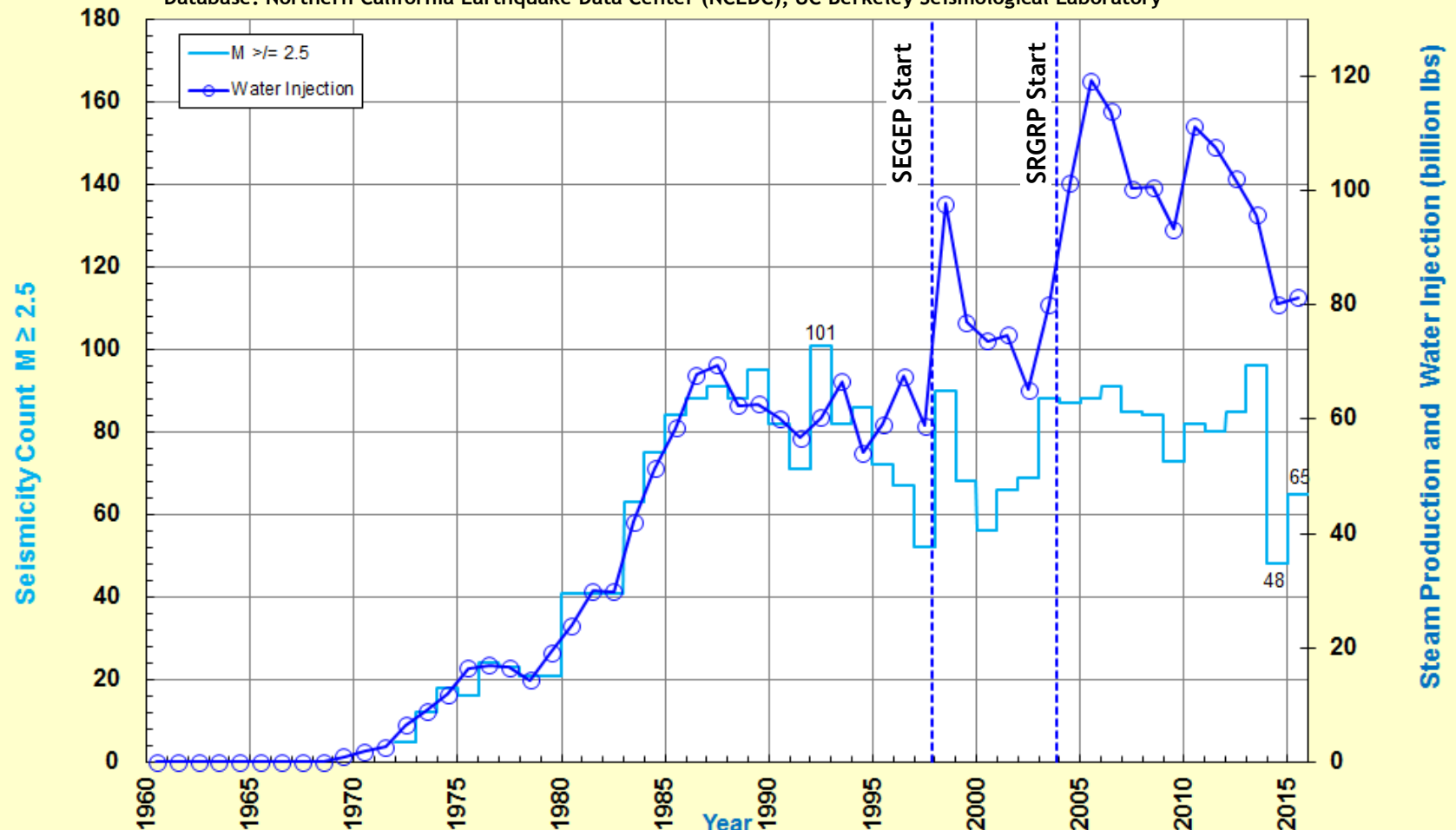
* Seismic event counts projected for final 113 days of 2015 (since Valley Fire on September 12, 2015)
Water injection and steam production values projected for final four months of 2015 (Since 01 September 2015)

Seismic Monitoring Advisory Committee Meeting

Yearly Field-wide Water Injection and $M \geq 2.5$ Seismicity 1960 Through End 2015 - Projected

The Geysers: Field-wide Water Injection and $M \geq 2.5$ Seismicity 1960 through end 2015 *

Database: Northern California Earthquake Data Center (NCEDC); UC Berkeley Seismological Laboratory



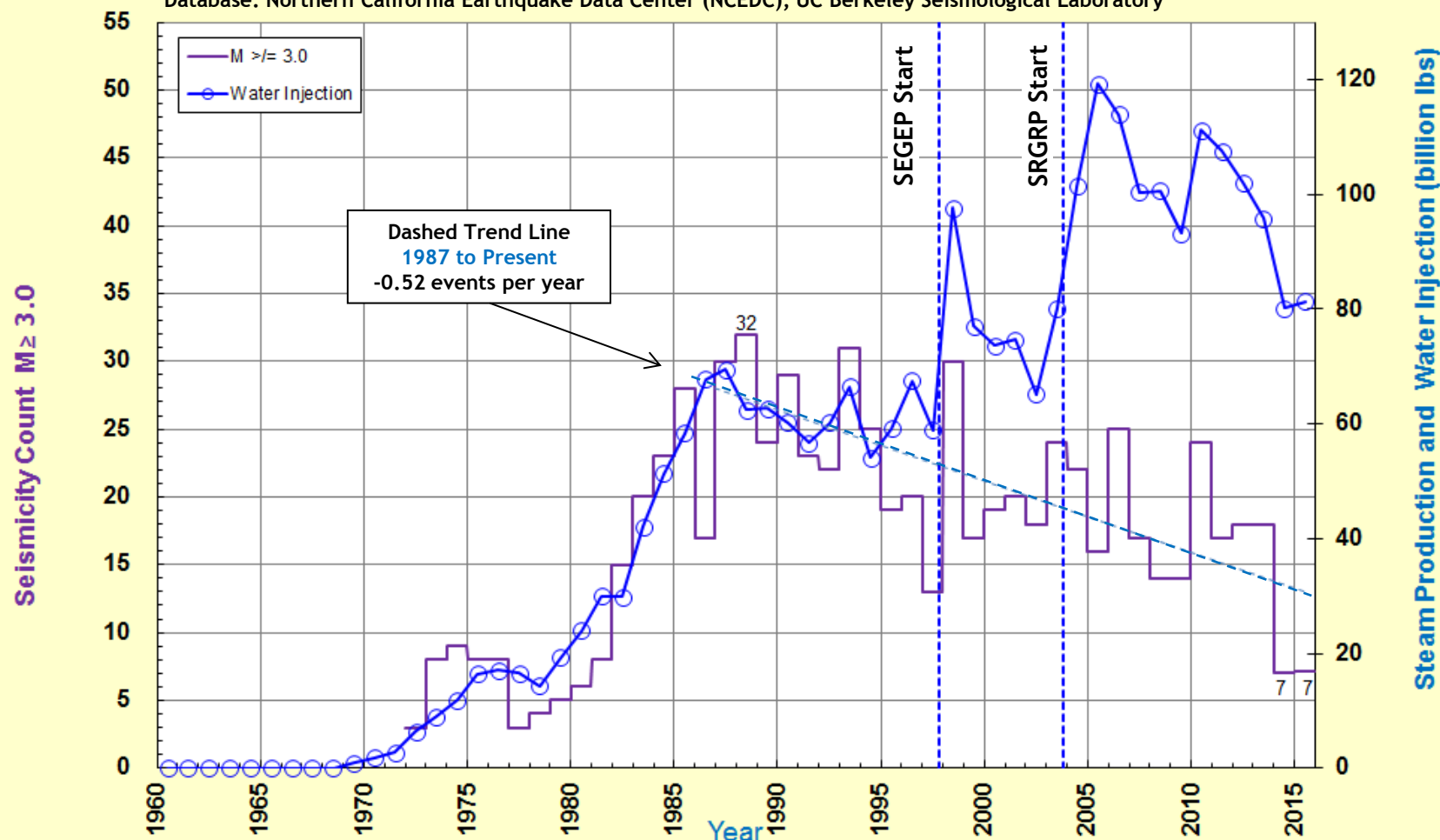
* Seismic event counts projected for final 113 days of 2015 (since Valley Fire on September 12, 2015)
Water injection and steam production values projected for final four months of 2015 (Since 01 September 2015)

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Yearly Field-wide Water Injection and $M \geq 3.0$ Seismicity 1960 Through End 2015 - Projected

The Geysers: Field-wide Water Injection and $M \geq 3.0$ Seismicity 1960 through end 2015 *

Database: Northern California Earthquake Data Center (NCEDC); UC Berkeley Seismological Laboratory



* Seismic event counts projected for final 113 days of 2015 (since Valley Fire on September 12, 2015)
Water injection and steam production values projected for final four months of 2015 (Since 01 September 2015)

Seismic Monitoring Advisory Committee Meeting

Field-wide Water Injection Sources and Magnitude ≥ 4.0 Seismicity

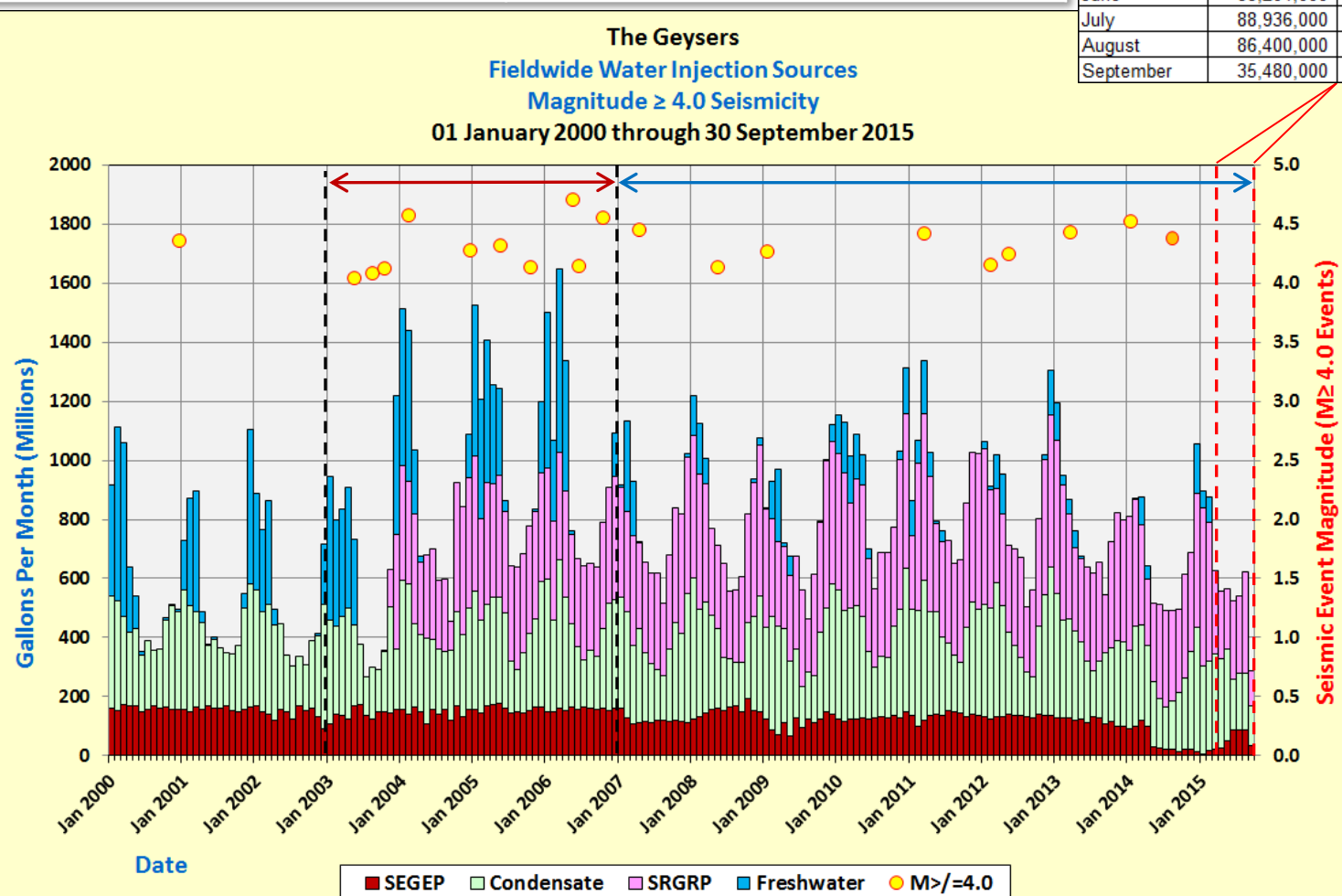
Monthly Values from 01 January 2000 to 30 September 2015



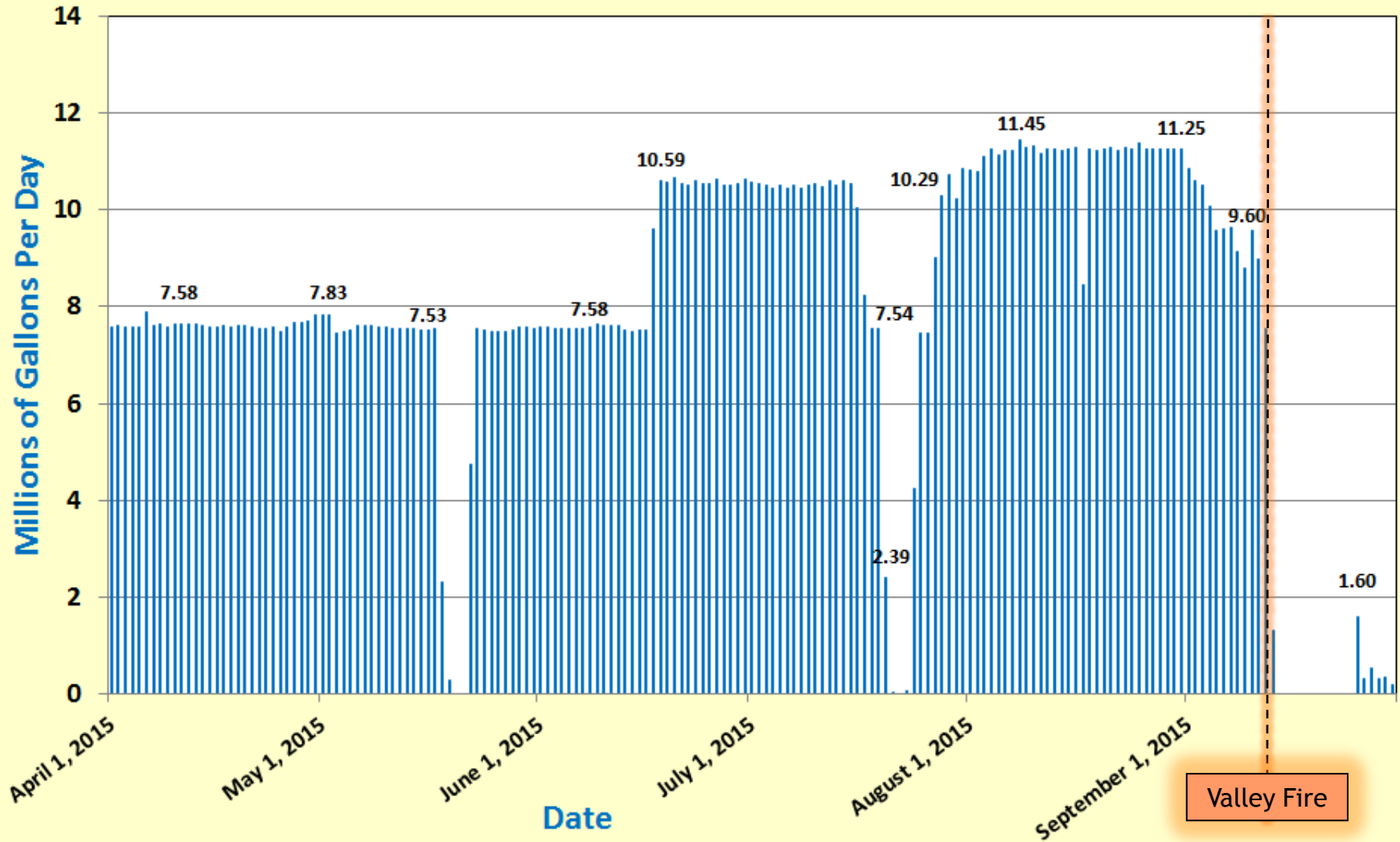
Average Number of Magnitude ≥ 4.0 Events Per Year Significantly Less Than 2003-2006 Peak

Time Period	M ≥ 4.0 Seismic Events	
January 2003 through December 2006	2.50 events per year	10.0 / 4.0
January 2007 through September 2014	1.03 events per year	9.0 / 8.75

Water Supply for Reporting Period (Six Months)				
Water Injection Sources (Gallons)				
Month	SEGE	SRGR	Condensate	Fresh Water
April	27,220,000	228,340,000	302,633,524	-
May	51,294,000	203,740,000	309,580,546	-
June	88,201,000	267,760,000	168,817,275	-
July	88,936,000	263,700,000	188,707,412	-
August	86,400,000	345,060,000	191,041,010	-
September	35,480,000	119,410,000	131,475,044	-



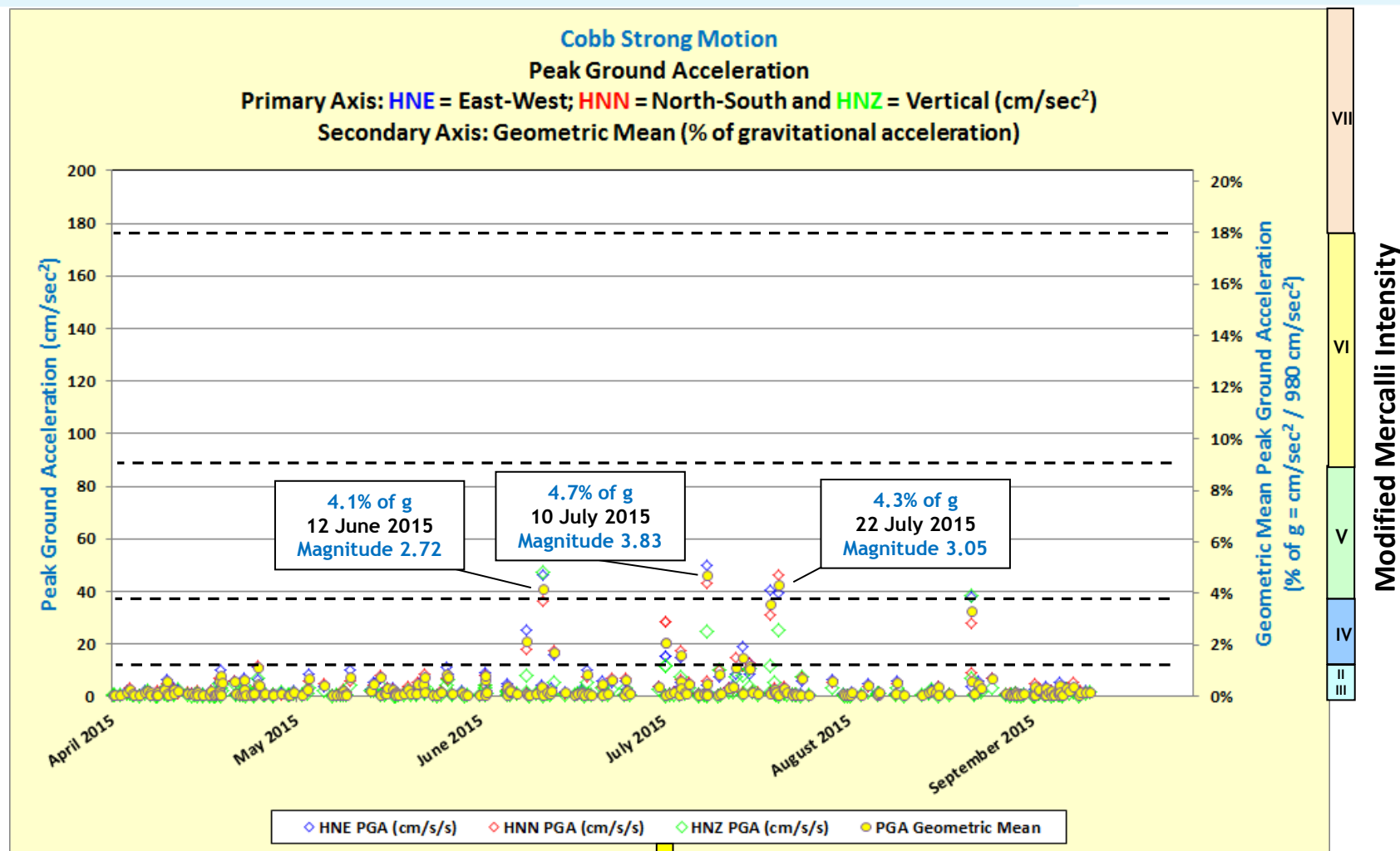
SRGRP Water Supply to Calpine Corporation 01 April 2015 to 30 September 2015



Seismic Monitoring Advisory Committee Meeting

Cobb Peak Ground Acceleration

01 April 2015 to 30 September 2015

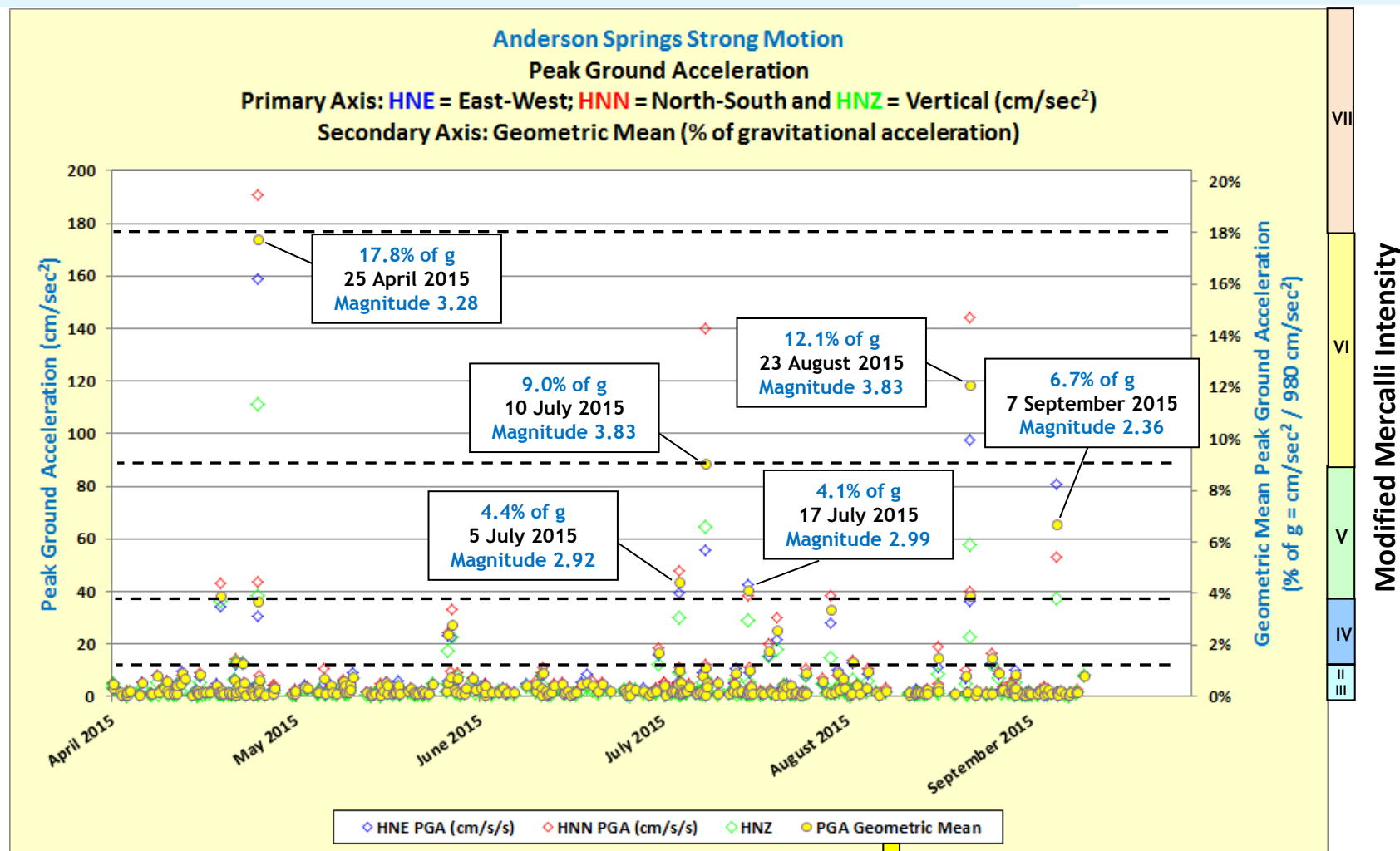


Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	None	None	None	Very Light	Light	Moderate	Mod/Heavy	Heavy	Very Heavy
Peak Acceleration (% of g)	< 0.17	0.17 - 1.4	1.4 - 3.9	3.9 - 9.2	9.2 - 18.0	18.0 - 34.0	34.0 - 65.0	65.0 - 124.0	> 124.0
Peak Velocity (cm/sec)	< 0.10	0.1 - 1.1	1.1 - 3.4	3.4 - 8.1	8.1 - 16.0	16.0 - 31.0	31.0 - 60.0	60.0 - 116.0	> 116.0
Modified Mercalli Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X

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Anderson Springs Peak Ground Acceleration

01 April 2015 to 30 September 2015

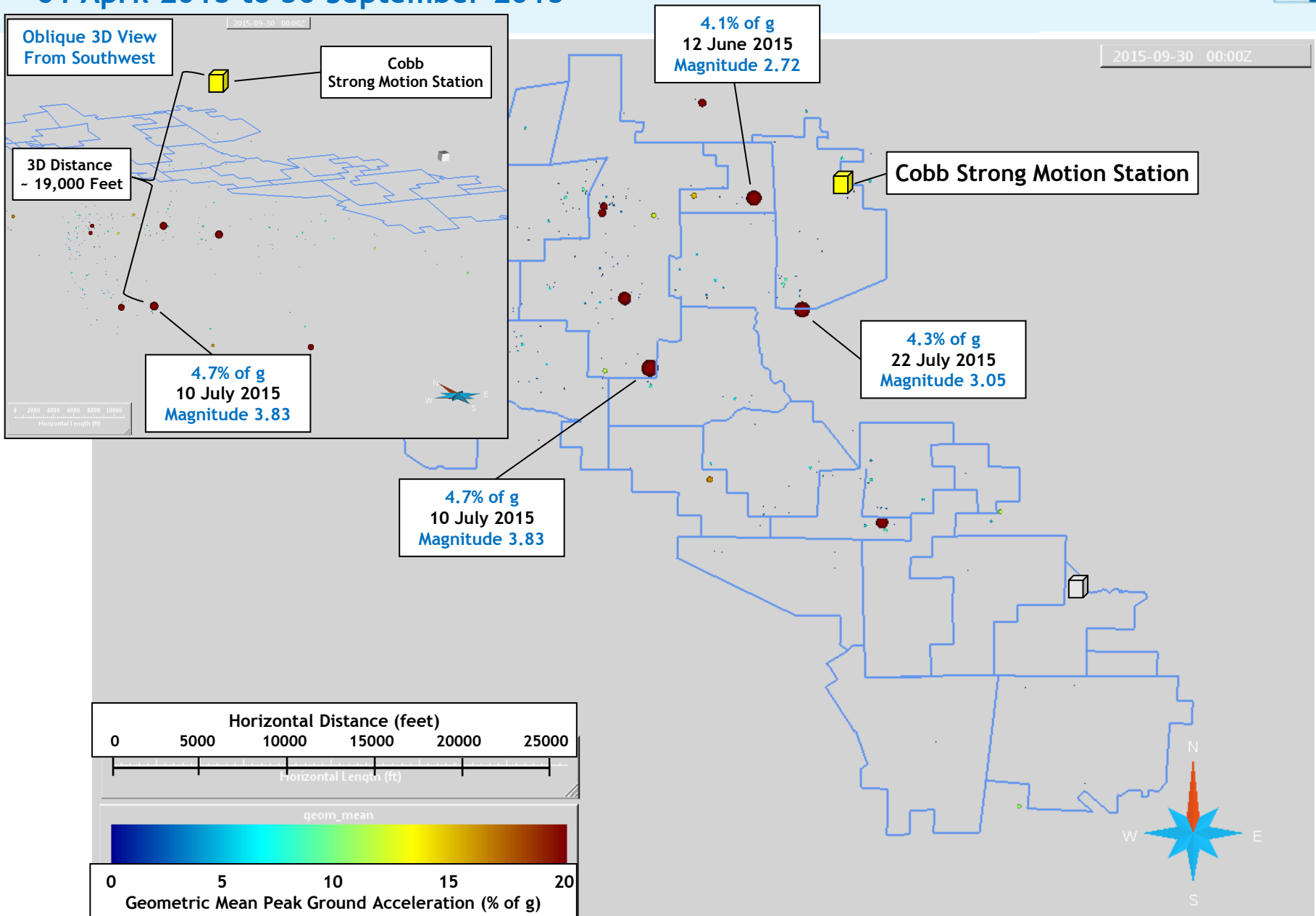


Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	None	None	None	Very Light	Light	Moderate	Mod/Heavy	Heavy	Very Heavy
Peak Acceleration (% of g)	< 0.17	0.17 - 1.4	1.4 - 3.9	3.9 - 9.2	9.2 - 18.0	18.0 - 34.0	34.0 - 65.0	65.0 - 124.0	> 124.0
Peak Velocity (cm/sec)	< 0.10	0.1 - 1.1	1.1 - 3.4	3.4 - 8.1	8.1 - 16.0	16.0 - 31.0	31.0 - 60.0	60.0 - 116.0	> 116.0
Modified Mercalli Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X

Seismic Monitoring Advisory Committee Meeting

Cobb Peak Ground Acceleration

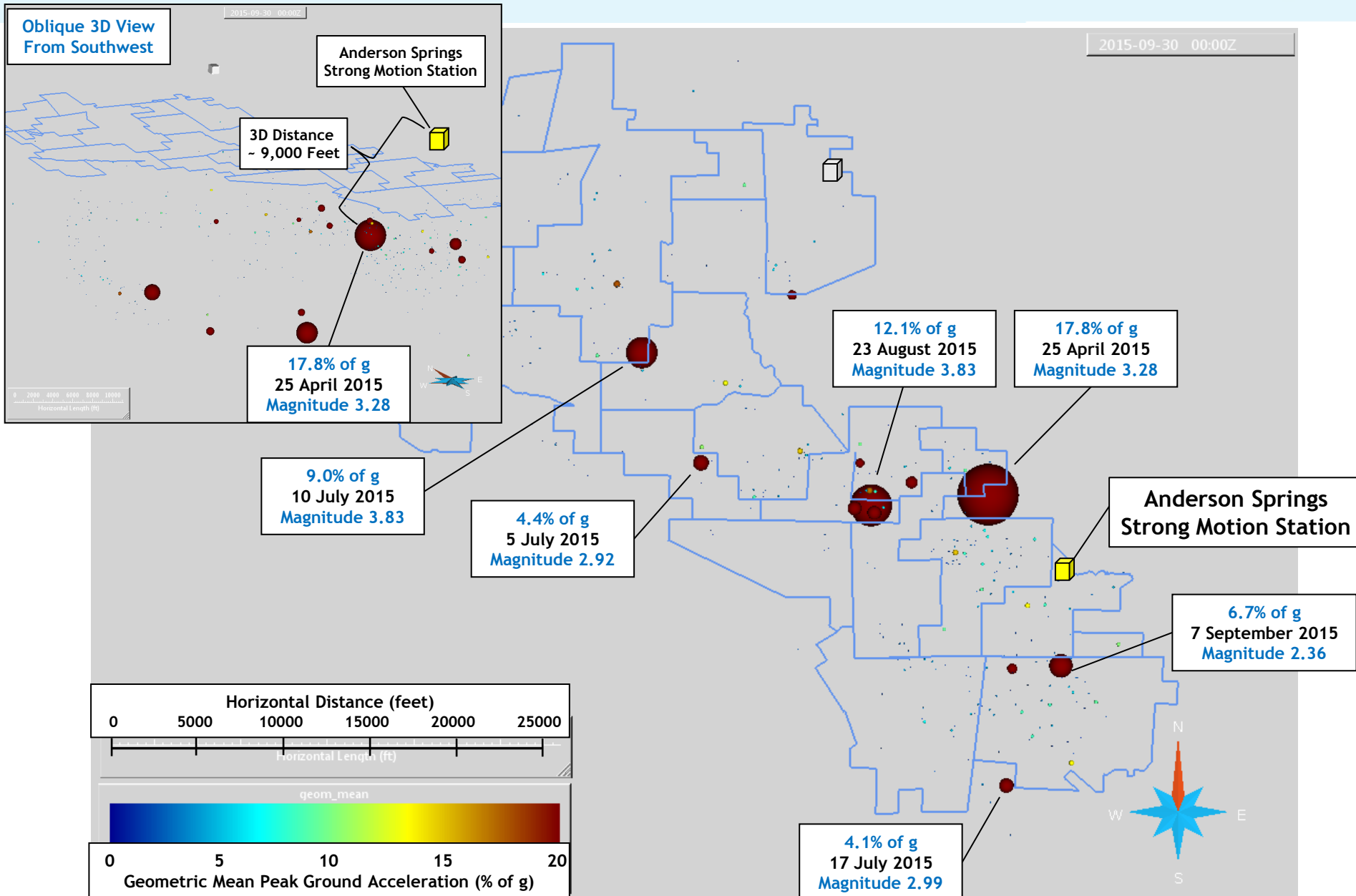
01 April 2015 to 30 September 2015



Seismic Monitoring Advisory Committee Meeting

Anderson Springs Peak Ground Acceleration

01 April 2015 to 30 September 2015



Seismic event magnitude is dependent on:

- Fault Area
- Average Slip
- Rock Rigidity

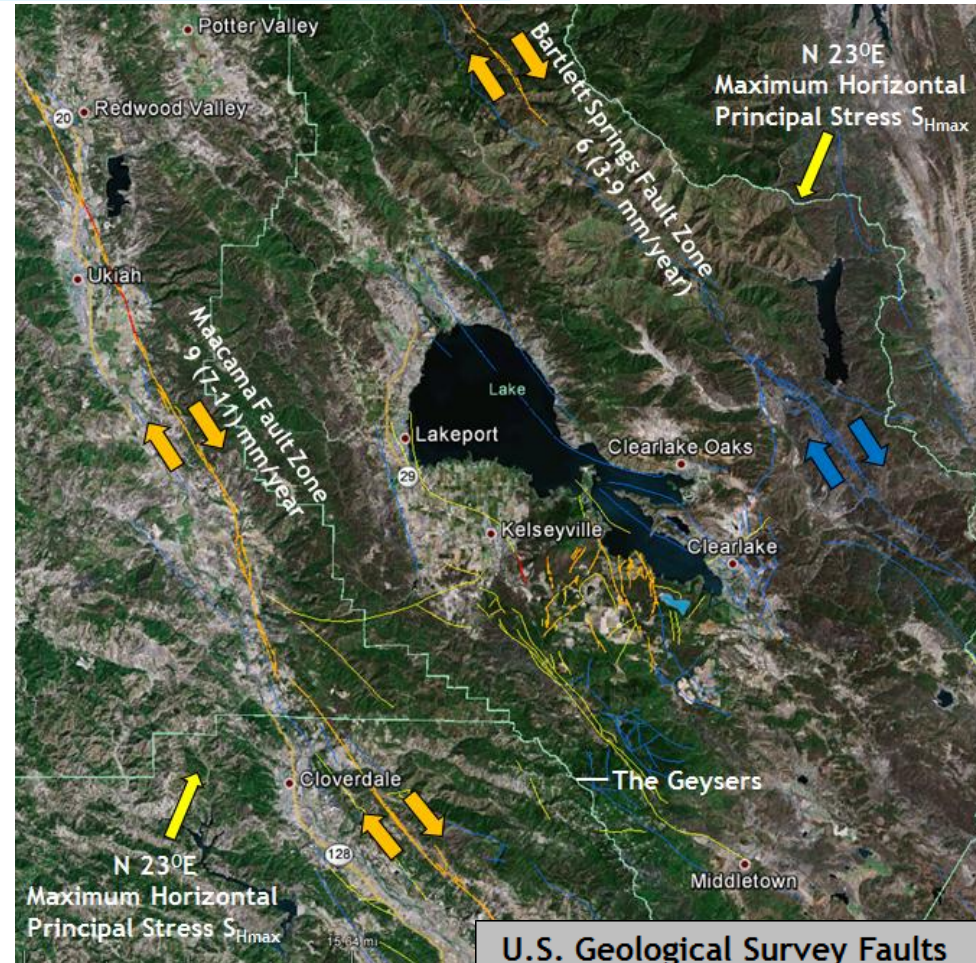
The Earth's crust is crossed by a network of pre-existing faults and fractures of various sizes.

Within The Geysers, CGS/USGS* mapped faults are inactive and restricted in area. This fact, along with highly-fractured steam reservoir (as defined by extensive drilling activities) provides confidence that there is not sufficient fault area to support a large earthquake (Majer et al, 2007).

A three-dimensional structural model is currently under development for The Geysers geothermal field.

This 3D structural model (including pre-existing fault zones and fractures) will assist in understanding induced seismicity at The Geysers.

* California Geological Survey, United States Geological Survey



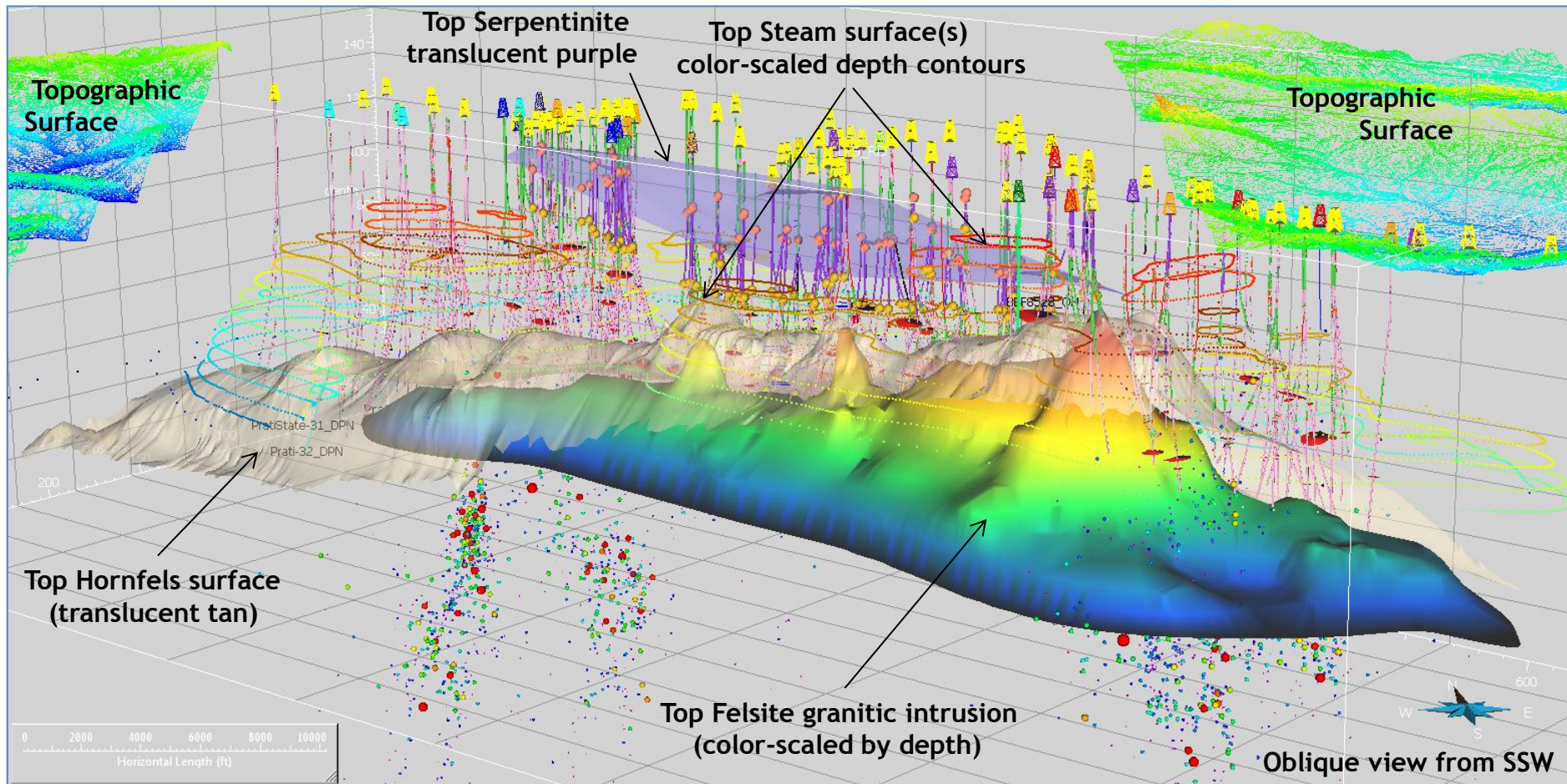
2012 Google Earth

U.S. Geological Survey Faults	
Time since fault motion	
<150 years	Red
<15,000 years	Orange
<130,000 years	Yellow
<750,000 years	Green
<1,600,000 years	Blue

Seismic Monitoring Advisory Committee Meeting

3D Visualization and Model Building

Regional Model



Two selected northwest-to-southeast well track "corridors" are displayed with assigned lithology (rock type).

Steam entries displayed as **red disks** (scaled by stream pressure increase).

Seismicity is displayed for 2500' wide southwest-to-northeast oriented corridors in the:

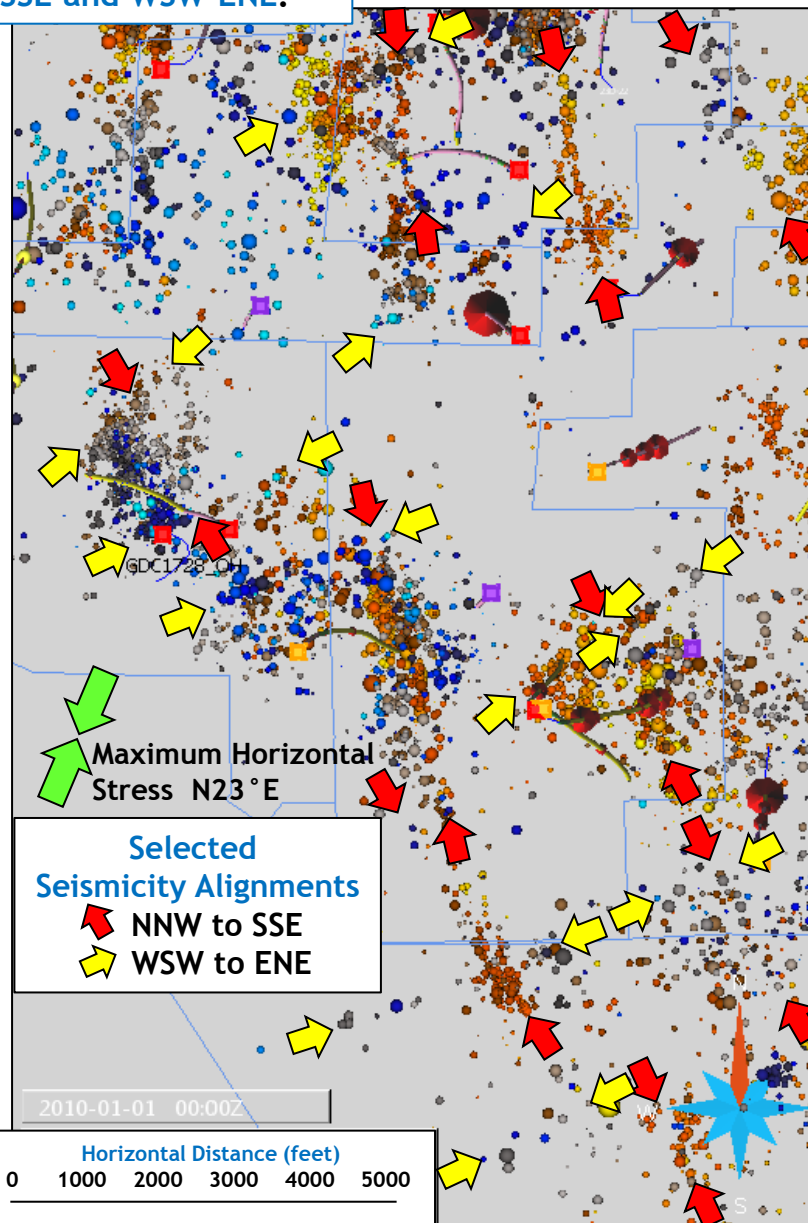
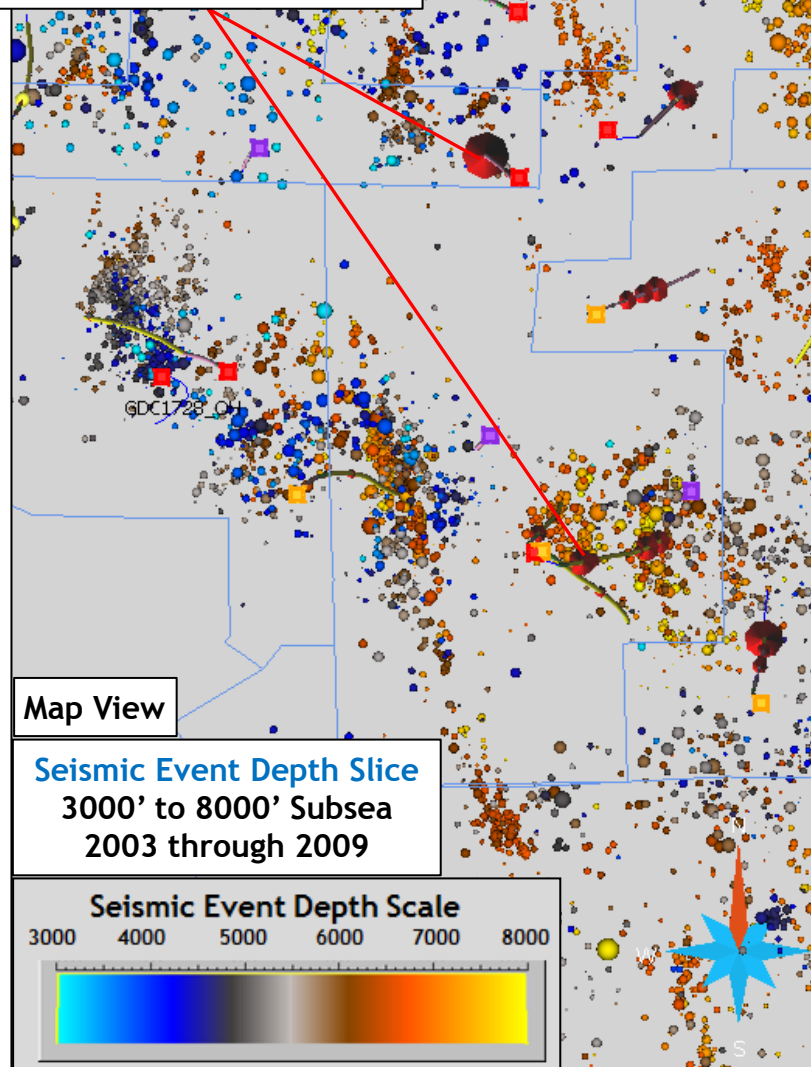
(1) Northwest Geysers NW04

(2) Southeast Geysers SE09

Vertical exaggeration of 1.25 x

The Geysers reservoir is subdivided by intersecting zones of faulting and fracturing, the majority of which are oriented NNW-SSE and WSW-ENE.

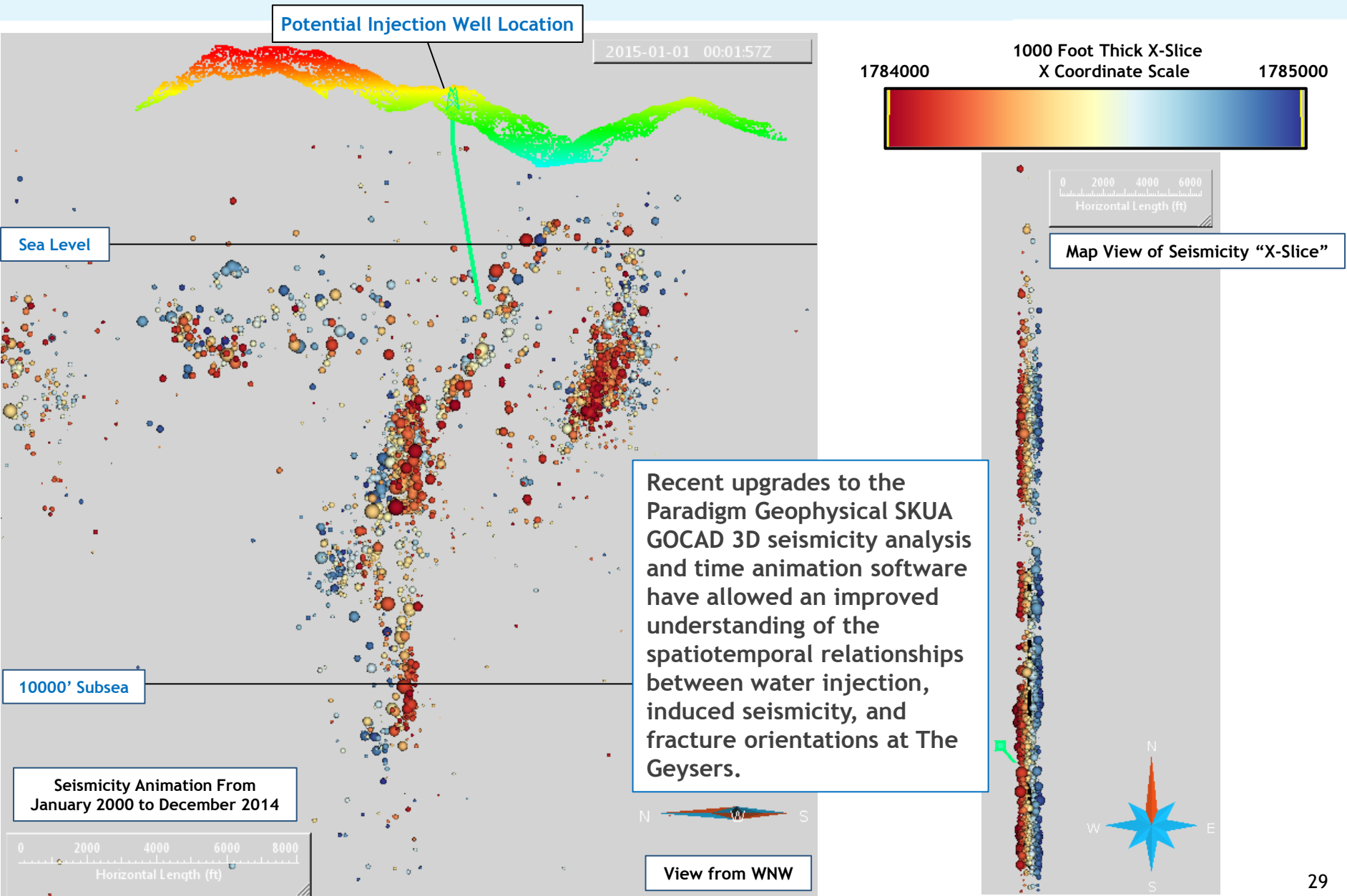
Injection Well Tracks
Red Disks = Steam Entries
(scaled by PSI)



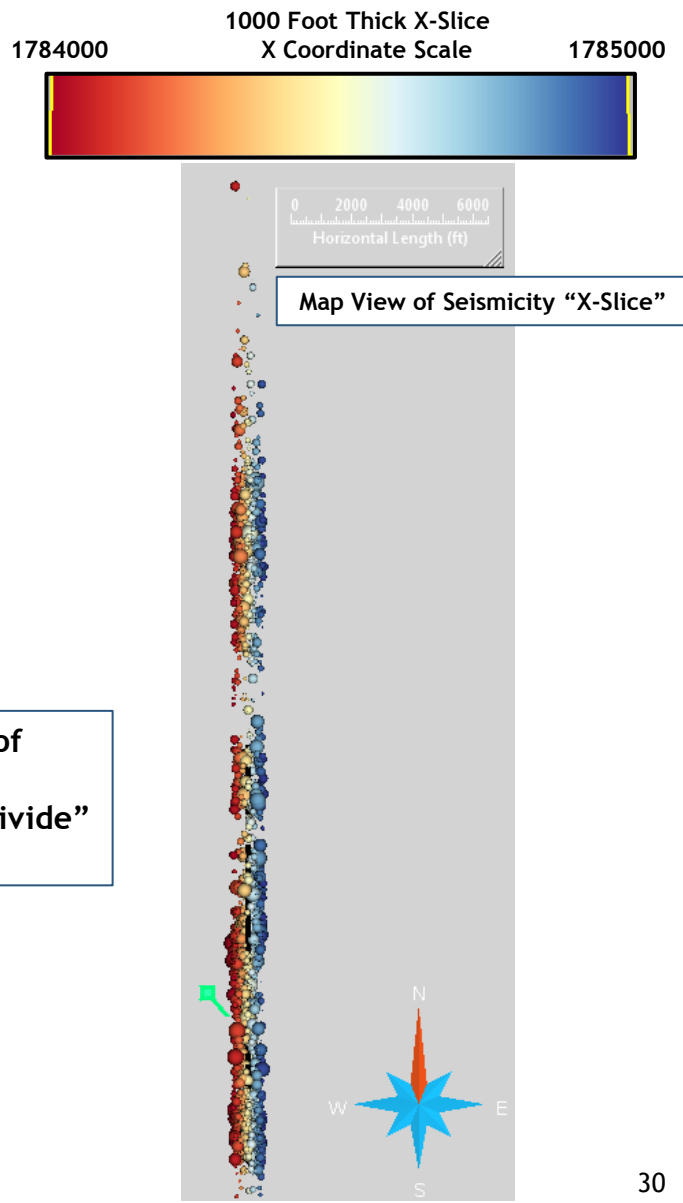
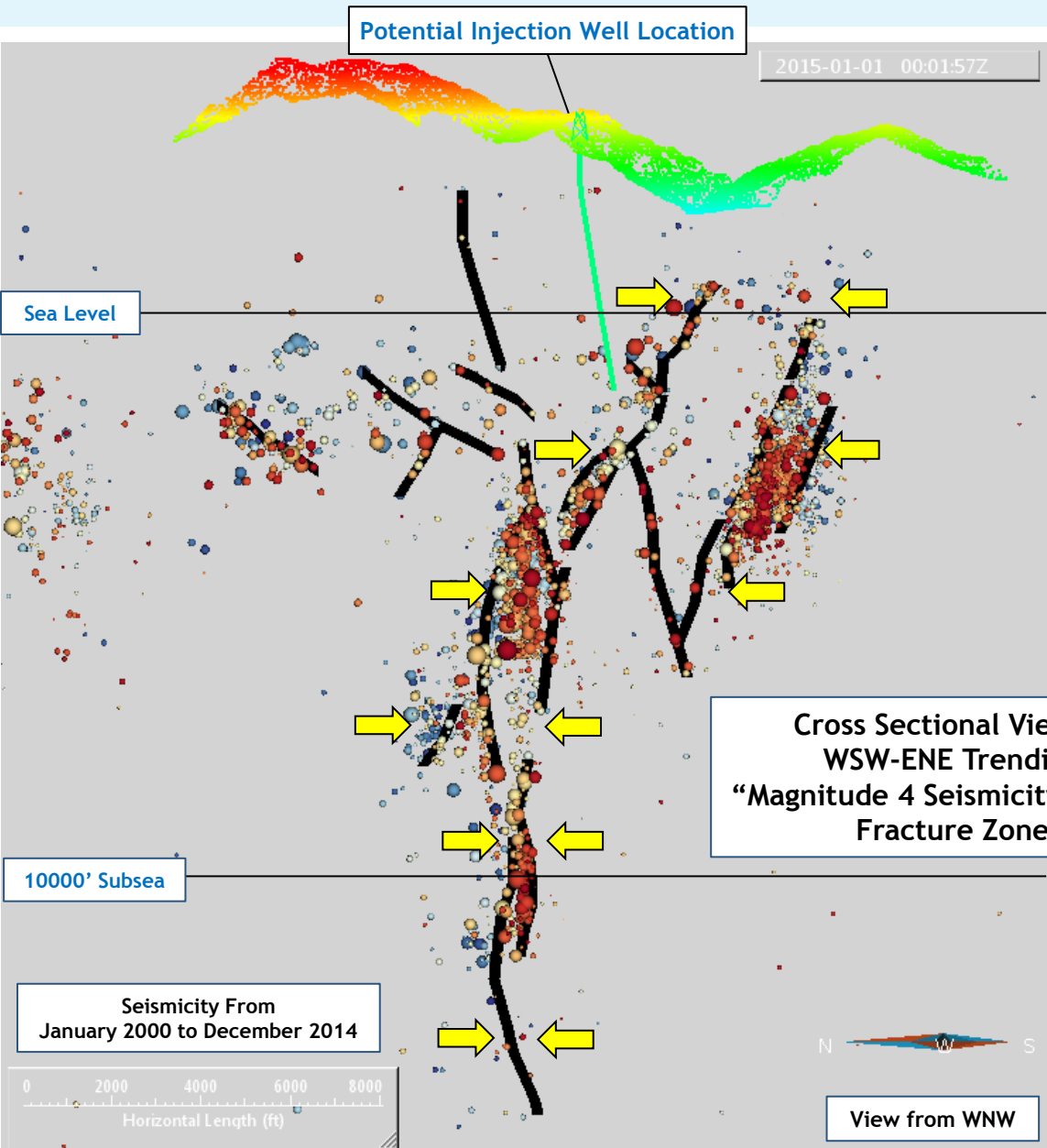
Seismic Monitoring Advisory Committee Meeting

Calpine 3D Visualization and 3D Structural Model Building

Fracture Zone Interpretation; South Central Geysers

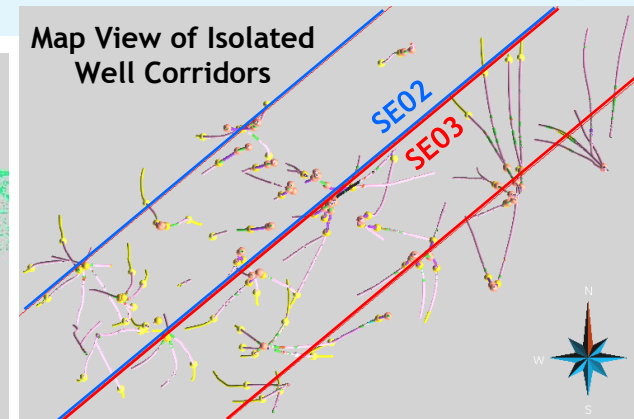
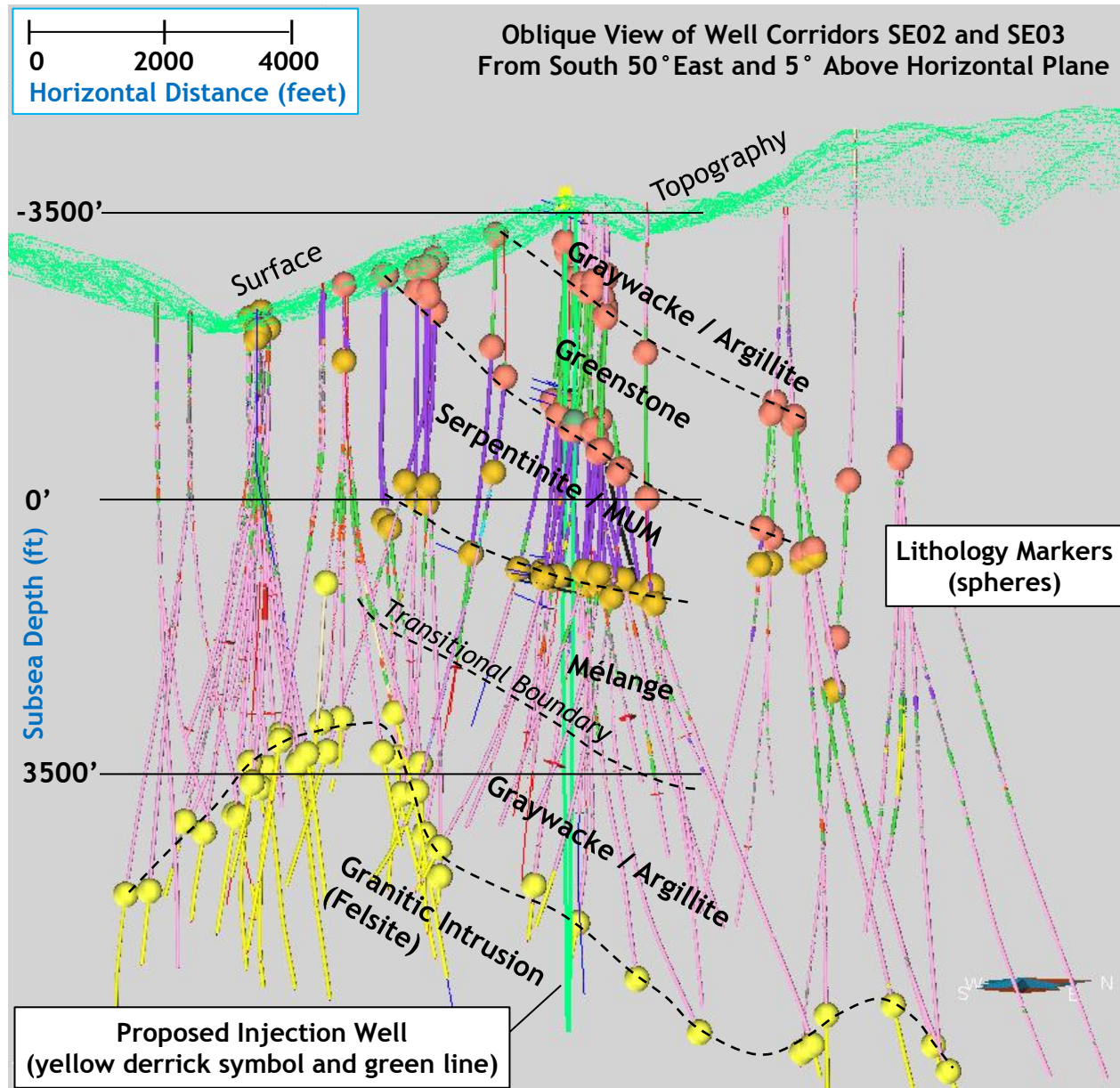


Seismic Monitoring Advisory Committee Meeting
Calpine 3D Visualization and 3D Structural Model Building
Fracture Zone Interpretation; South Central Geysers



Seismic Monitoring Advisory Committee Meeting

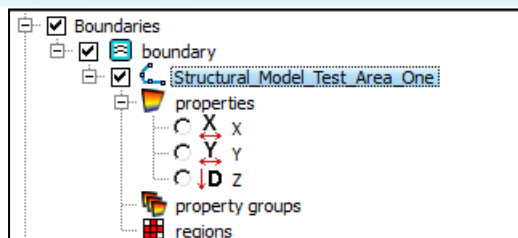
3D Structural Model Building at The Geysers



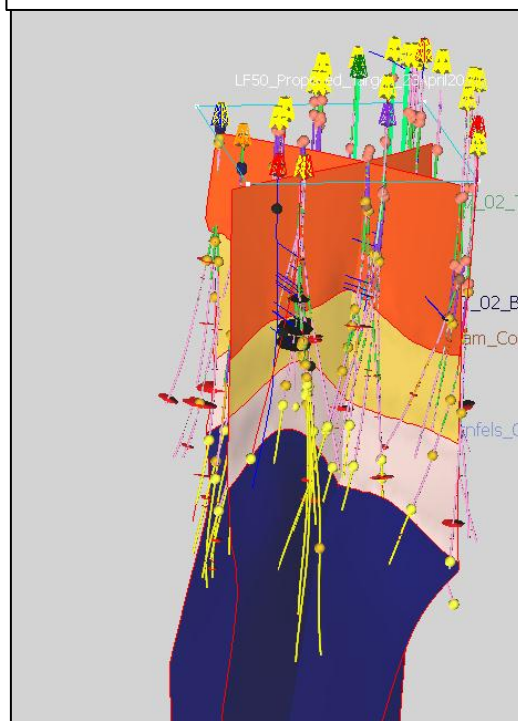
Seismic Monitoring Advisory Committee Meeting

3D Visualization and Model Building

Detailed 3D Structural Interpretation



Detailed 3D Test Area Central Geysers



Paradigm Geophysical SKUA GOCAD 3D software is now being utilized for detailed local 3D model building.

Individual Well Induced Seismicity Studies

Fluid Flow Paths and Barriers

Local Geologic Structure

Reservoir Geometry

Reservoir Compartmentalization

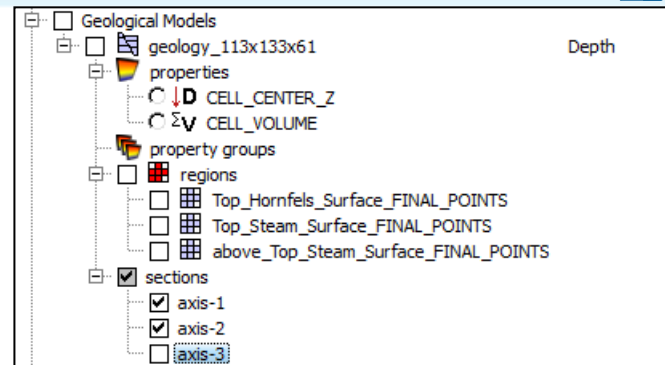
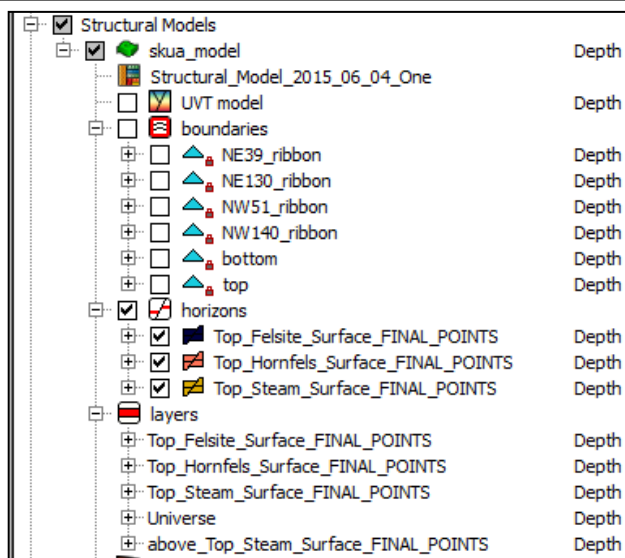
Reservoir Management

3D Well Planning

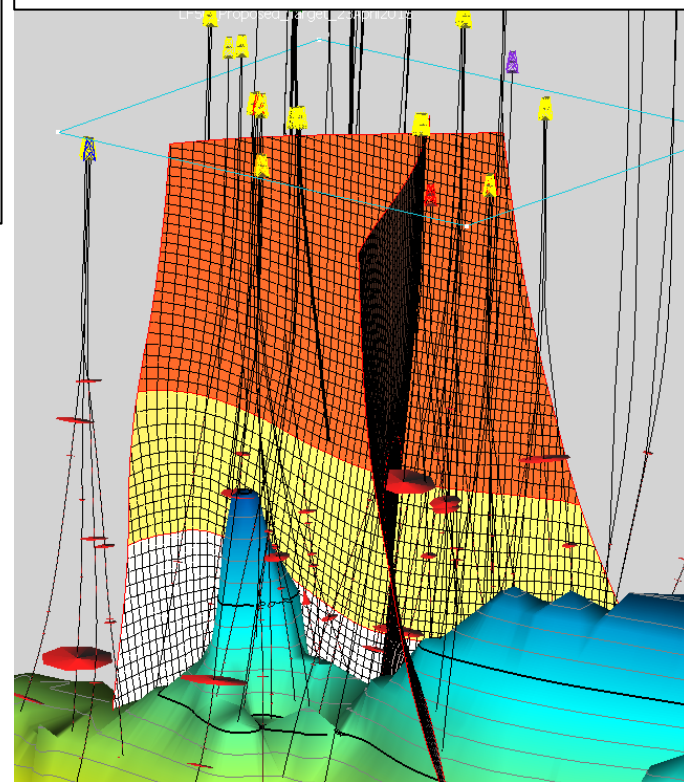
3D Real-Time Drilling Analysis

Providing the Structural Framework for a Refined 3D Reservoir Model

(for use by Calpine's Reservoir Engineers)



Detailed 3D Test Area Central Geysers Cell-based Structural Model



Seismic Monitoring Advisory Committee Meeting

Seismicity Monitoring Research

Borehole Fiber Optic Seismic Sensor Program #1

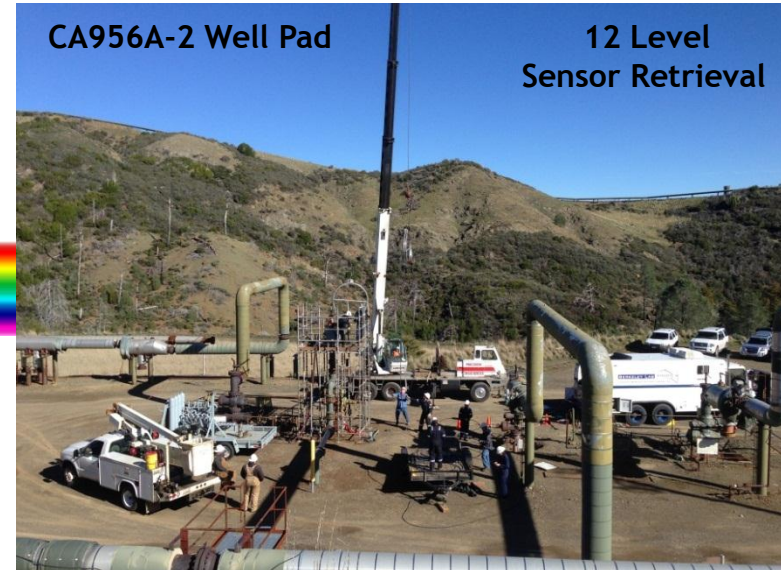
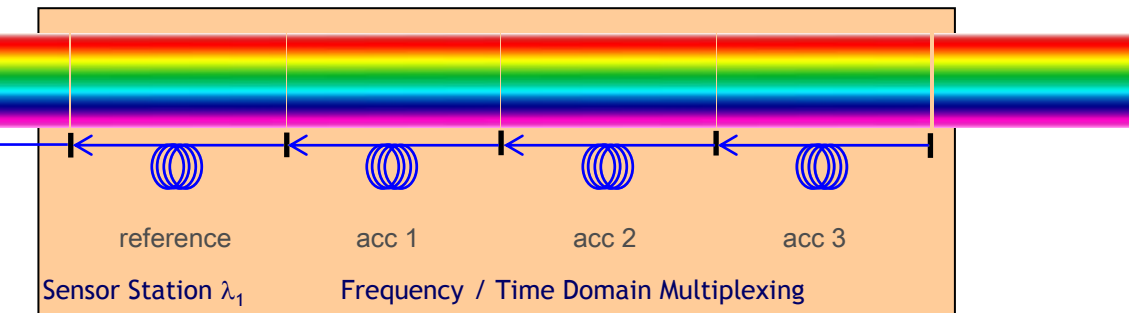


Calpine Corporation is promoting the development of “next-generation” three-component fiber optic seismic sensor technologies suitable for high-temperature boreholes and providing improved seismic data resolution.

Fiber Bragg Gratings

The fiber is the sensor - no electronics below ground surface!

- *powered by light - reflects light of a specific wavelength*
- *other wavelengths transmitted*



1) United States Seismic Systems Incorporated / Calpine / LBNL*

Test completed 20 January 2015 at CA-956A-2 (Southeast Geysers)

12 level / 36 sensor high-temperature (215°C / 419°F)

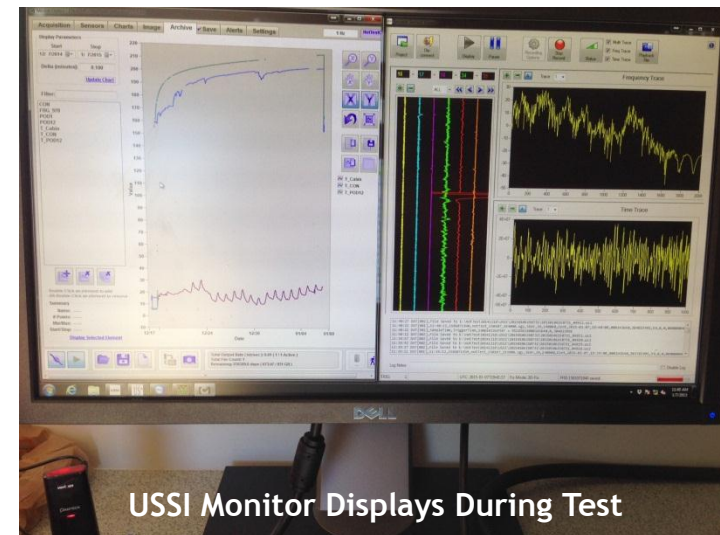
Maximum depth: 4350 feet

Long-term high temperature borehole deployment.

Gases generated by protective gel within sensor pods.

Deteriorated silicon-based sensor pod seals.

Design modifications resulted.



* Lawrence Berkeley National Laboratory

Seismic Monitoring Advisory Committee Meeting

Seismicity Monitoring Research

Borehole Fiber Optic Seismic Sensor Program #2

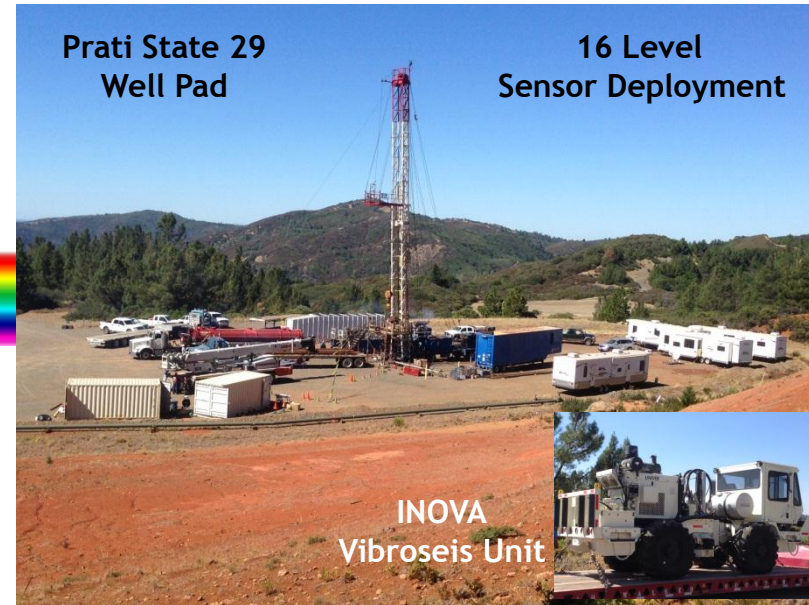
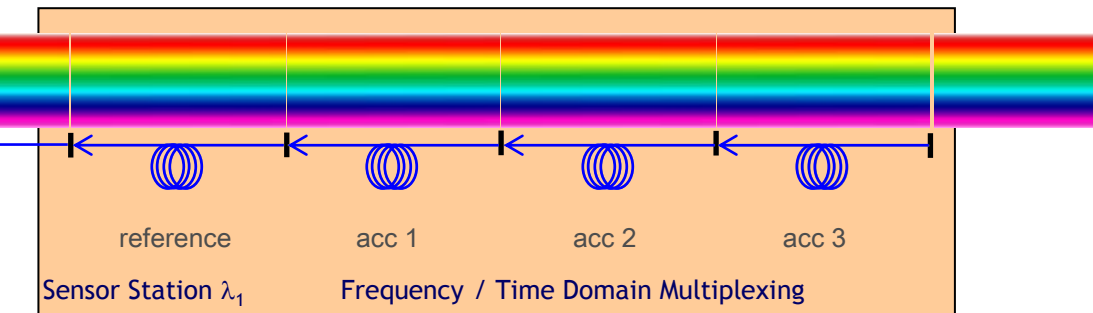


Calpine Corporation is promoting the development of “next-generation” three-component fiber optic seismic sensor technologies suitable for high-temperature boreholes and providing improved seismic data resolution.

Fiber Bragg Gratings

The fiber is the sensor - no electronics below ground surface!

- *powered by light - reflects light of a specific wavelength*
- *other wavelengths transmitted*



2) Paulsson Incorporated / Calpine / LBNL*

Research funding provided by California Energy Commission; Calpine provides test location(s)
16 level / 48 sensor sensitivity test completed 12 September 2015 at Prati State 29 (northwest Geysers)

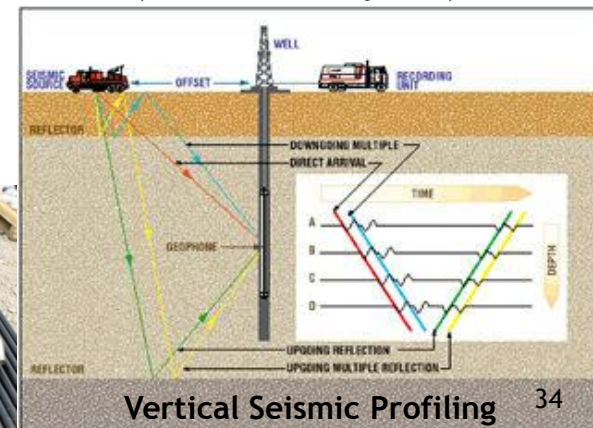
- Passive induced seismicity monitoring
- Active vertical seismic profile (VSP) imaging (with a “Vibroseis” energy source)

Operationally complicated program
Seismic data analysis in progress ...

Additional (*and much simplified*) testing proposed for southeast Geysers “MSA-5” borehole.

* Lawrence Berkeley National Laboratory

Sensor
Pods



Vertical Seismic Profiling

Research Collaboration: Early Detection and Warning System for Natural Earthquakes

Primary Goal

Automated control (and shutdown) of natural gas, electricity and water supply for refineries, chemical plants, public schools, medical facilities, ...



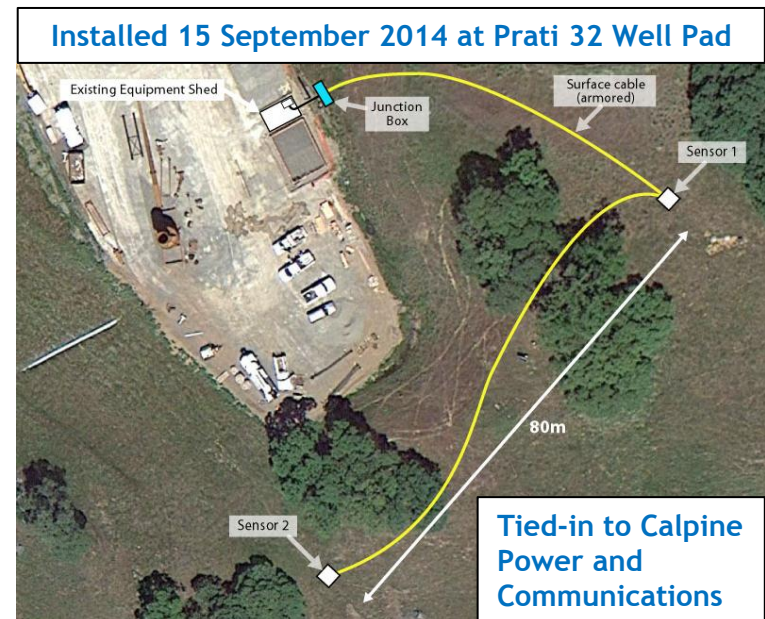
Geysers Project Goal

Refinement of event detection software to:

- Avoid false positives (caused by human activity)
- Distinguish between:
 - **Smaller seismic events** typical of The Geysers
These should be ignored
 - **Large seismic events** (earthquakes)
Triggering automated warnings and shutdowns

Project Update - 05 November 2015

- Have recorded excellent data allowing refinement of seismic event detection and hypocenter determination algorithms.
- Seismic Warnings Systems wishes to install a second site to the southeast of the existing station.



RESEARCH ARTICLE

10.1002/2015JB012362

Key Points:

- Analyzed long-term changes in characteristics of induced seismicity
- Seismicity characteristics reflect fluid migration and increasing pore pressure
- Maximum magnitude related to injection rate and volume of fluids present in reservoir

Supporting Information:

- Text S1

Correspondence to:G. Kwiatek,
kwiatek@gfz-potsdam.de**Citation:**

Kwiatek, G., P. Martínez-Garzón, G. Dresen, M. Bohnhoff, H. Sone, and C. Hartline (2015), Effects of long-term fluid injection on induced seismicity parameters and maximum magnitude in northwestern part of The Geysers geothermal field, *J. Geophys. Res. Solid Earth*, 120, doi:10.1002/2015JB012362.

Received 15 JUL 2015

Accepted 28 SEP 2015

Accepted article online 2 OCT 2015

Effects of long-term fluid injection on induced seismicity parameters and maximum magnitude in northwestern part of The Geysers geothermal field

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²Institute of Earth and Environmental Sciences, University of Potsdam, Potsdam, Germany, ³Institute of Geological Sciences, Free University Berlin, Berlin, Germany, ⁴Department of Civil and Environmental Engineering, Geological Engineering Program, University of Wisconsin-Madison, Madison, Wisconsin, USA, ⁵Calpine Corporation, Middletown, California, USA

Abstract The long-term temporal and spatial changes in statistical, source, and stress characteristics of one cluster of induced seismicity recorded at The Geysers geothermal field (U.S.) are analyzed in relation to the field operations, fluid migration, and constraints on the maximum likely magnitude. Two injection wells, Prati-9 and Prati-29, located in the northwestern part of the field and their associated seismicity composed of 1776 events recorded throughout a 7 year period were analyzed. The seismicity catalog was relocated, and the source characteristics including focal mechanisms and static source parameters were refined using first-motion polarity, spectral fitting, and mesh spectral ratio analysis techniques. The source characteristics together with statistical parameters (b value) and cluster dynamics were used to investigate and understand the details of fluid migration scheme in the vicinity of injection wells. The observed temporal, spatial, and source characteristics were clearly attributed to fluid injection and fluid migration toward greater depths, involving increasing pore pressure in the reservoir. The seasonal changes of injection rates were found to directly impact the shape and spatial extent of the seismic cloud. A tendency of larger seismic events to occur closer to injection wells and a correlation between the spatial extent of the seismic cloud and source sizes of the largest events was observed suggesting geometrical constraints on the maximum likely magnitude and its correlation to the average injection rate and volume of fluids present in the reservoir.

1. Introduction

The need to refine and further develop reservoir engineering techniques such as stimulation of geothermal and (un)conventional hydrocarbon reservoirs, exploitation of deep mines, and underground storage facilities poses fundamental challenges to be addressed such as mitigation of induced seismicity (Ellsworth, 2013). Of special concern in studies of induced seismicity are large magnitude events (LME). LMEs might pose a threat to engineering structures, raise public-acceptance issues, or even cause casualties among underground workers in mines. A striking example is the occurrence of LMEs related to reservoir stimulation within the geothermal Deep Heat Mining project in Basel. A 6 day lasting stimulation of the reservoir for geothermal power production at 5 km depth resulted in occurrence of more than 10,000 seismic events with local magnitudes $M_L > 0.6$ including several magnitude ~ 3.4 earthquakes (Deichmann and Giardini, 2009). The seismicity was widely felt by the local population raising over \$9M insurance claims and resulting in the shutdown of the project (Giardini, 2009). Recently, the occurrence of LMEs has been reported from hydraulic fracturing operations in south-central Oklahoma (Holland, 2013); waste-water disposal in central Arkansas (Horton, 2012); fluid injection in Youngstown, Ohio (Kim, 2013); induced seismicity during the construction of Gotthard Base Tunnel (Husen et al., 2012); gas storage (Cesca et al., 2014); or shale gas fracturing at Blackpool, UK (Evans et al., 2012). Despite the clear economic and societal relevance of LMEs, a profound understanding of the physical processes leading to their occurrence in response to engineering operations is still lacking.

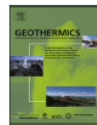
Mitigation of seismic hazard from induced seismicity is of utmost importance for a safe and efficient (renewable) energy production and development. One of the most debated issues in seismic hazard studies related to induced seismicity is estimating the maximum likely event magnitude (Convertito et al., 2012). The proposed methods may be divided into deterministic, probabilistic, and empirical [e.g., Zang et al., 2014]. Classical probabilistic seismic hazard assessment procedures require an earthquake catalog and need to account



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Geothermics

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The Northwest Geysers EGS Demonstrations Project, California Part 1: Characterization and reservoir response to injection

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ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form 4 August 2015
Accepted 5 August 2015
Available online xxx

Keywords:
Enhanced Geothermal Systems
The Geysers
Induced seismicity
Reservoir stimulation
Shear zones

ABSTRACT

An Enhanced Geothermal System (EGS) Demonstration Project is currently underway in the Northwest Geysers. The project goal is to demonstrate the feasibility of stimulating a deep high-temperature reservoir (HTR) (up to 400 °C, 750 °F). Two previously abandoned wells, Prati State 31 (PS-31) and Prati 32 (P-32), were reopened and deepened to be used as an injection and production doublet to stimulate the HTR. The deepened portions of both wells have conductive temperature gradients of 10 °F/100 ft (182 °C/km), produce connate native fluids and magmatic gas, and the rocks were isotopically unexchanged by meteoric water. The ambient temperature meteoric water injected into these hot dry rocks has evidently created a permeability volume of several cubic kilometers as determined by seismic monitoring. Preliminary isotopic analyses of the injected and produced water indicate that 50–75% of the steam from the created EGS reservoir is injection-derived.

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1. Introduction

The Geysers Geothermal field is the world's largest geothermal electricity generating operation and has been in commercial operation since 1960. It is a vapor-dominated geothermal reservoir system that was developed to a maximum installed capacity of 2043 MWe by 1987. Subsequently, a number of peripheral developed areas were abandoned because of resource problems including declining steam pressure, low permeability, corrosive steam and high non-condensable gas (NCG) concentrations. As a result of the high steam withdrawal rates, the reservoir pressure declined until the mid 1990s, when increasing injection rates resulted in a stabilization of the steam production and reservoir pressure. In recent decades, operators have been relying heavily on supplemental water injection to sustain its current generation of 825 MWe.

The concept of Enhanced Geothermal Systems (EGS) at The Geysers differs from other EGS programs pursued elsewhere in the world. At The Geysers, EGS projects target areas which contain a significant portion of the recoverable geothermal energy in the system that is currently underutilized. The main focus is on the

revival of production from peripheral areas by using water injection to increase reservoir pressure, increase permeability, reduce NCG concentrations and mitigate corrosion. Although this scope is somewhat site-specific, the vast unexploited heat resource and existing infrastructure at The Geysers offers an opportunity for significant short-term EGS generation.

The EGS Demonstration Project is in the northwestern portion of The Geysers geothermal field (Fig. 1) where a high temperature reservoir (HTR) with temperatures up to 400 °C (750 °F) was previously identified (Walters et al., 1992; Walters and Beall, 2002). The HTR underlies a normal temperature reservoir (NTR) where temperatures are about 240 °C (465 °F).

The EGS Demonstration Project area was originally explored in the 1980s with three exploration and development wells in the Central California Power Agency (CCPA) steam field. These wells were never produced due to high concentrations of NCG produced from the HTR and were abandoned in 1999 after the CCPA #1 Power Plant was closed for economic reasons and later decommissioned.

Two of the previously abandoned wells, Prati State 31 (PS-31) and Prati 32 (P-32), were reopened, deepened and re-completed in 2010 for direct injection and stimulation of the HTR. The NTR in the project area is relatively shallow (the base of the NTR is at an elevation of ~1800 m mean sea level (m-MSL), ~6000 ft (ft-MSL)) and the project wells are sufficiently deep to penetrate the upper portion of the HTR (Fig. 1).

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Three-Dimensional Structural Model Building, Induced Seismicity Analysis, Drilling Analysis, and Reservoir Management at The Geysers Geothermal Field, Northern California

Craig S. Hartline, Mark A. Walters, and Melinda C. Wright

Calpine Corporation, The Geysers

Keywords

3D Visualization, 3D model building, induced seismicity, reservoir management, The Geysers

ABSTRACT

Calpine has adopted the use of Paradigm Geophysical SKUA GOCAD software originally developed for the oil and gas industry in its 3D visualization and model building of The Geysers geothermal reservoir. Structural model building constraints include lithology logs, temperature logs, pressure logs, tracer analysis patterns, heat flow patterns, reservoir history matching, surface geologic maps and seismicity hypocenters available from the Northern California Earthquake Data Center (NCEDC) and Lawrence Berkeley National Laboratory (LBNL). Recent upgrades to the Paradigm Geophysical SKUA GOCAD 3D seismicity analysis and time animation software have allowed an improved understanding of the spatiotemporal relationships between water injection, induced seismicity, and fracture orientations at The Geysers. This in turn provides a refined understanding of fluid flow paths, fluid boundaries, reservoir heterogeneity and compartmentalization at The Geysers. We can now demonstrate The Geysers reservoir is subdivided by intersecting zones of faulting and fracturing the majority of which are oriented NNW-SSE and ENE-WSW. The 3D structural model development is part of a program to more closely link geoscience, drilling and reservoir engineering, and is anticipated to contribute to reservoir management and induced seismicity mitigation efforts at The Geysers.

Background

The Geysers, located in Northern California and approximately 75 miles north of San Francisco, is the largest producing geothermal field in the world. Calpine Corporation operations at The Geysers include 14 geothermal plants, approximately 330 active steam production wells,

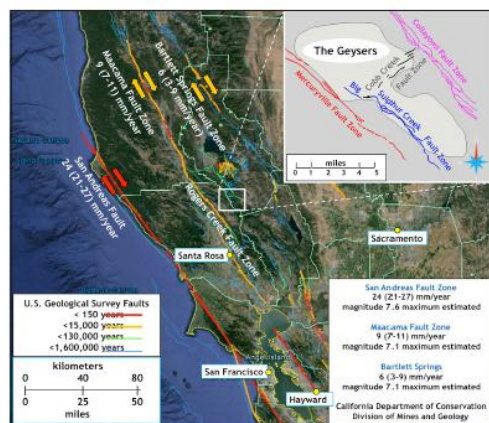


Figure 1. The San Andreas Fault System, including the Maacama / Rodgers Creek Fault Zone and Bartlett Spring Fault Zone. United States Geological Survey Faults with activity in the past 1.6 million years are displayed. Primary bounding fault zones are shown in the inset at upper right. This Google Earth image includes fault parameters from the California Division of Mines and Geology, 1996.

Lawrence Berkeley National Laboratory

- 32 station three-component permanent seismic monitoring network

- Collaboration on successful DOE co-funded EGS Demonstration Project, including two temporary seismic monitoring networks

- Collaboration on high-temperature tolerant borehole fiber optical seismic sensor testing

- Borehole seismic sensor installation and testing in the southeast Geysers

United States Geological Survey

- Geysers' seismicity processing and real-time availability, detailed analysis of magnitude ≥ 3.5 events

- Collaboration on full-waveform six-component (3 translational/3 rotational) seismic sensor testing

- Collaboration on Silicon Audio high-sensitivity optical accelerometer testing

Massachusetts Institute of Technology

- Collaboration on installation and operation of three continuous monitoring GPS instruments

Array Information Technology

- Research Collaborations with European GEISER Project

- Installation and recovery of 32 continuous broadband seismic recording instruments from GFZ Potsdam / GEISER Instrument Pool

GFZ Potsdam

- Collaboration on studies of spatiotemporal induced seismicity changes associated with variable water injection in the northwest Geysers

United States Seismic Systems

- High-temperature tolerant borehole fiber optical seismic sensor array test program

Paulsson Incorporated

- High-temperature tolerant borehole fiber optical seismic sensor array test program

- Active surface source vertical seismic profiling (VSP) test program

Seismic Warning Systems

- Calibration site for earthquake early warning systems in NW Geysers

