Seismic Monitoring Advisory Committee Meeting

01 October 2016 to 31 March 2017 Reporting Period

Calpine Geothermal Visitors Center

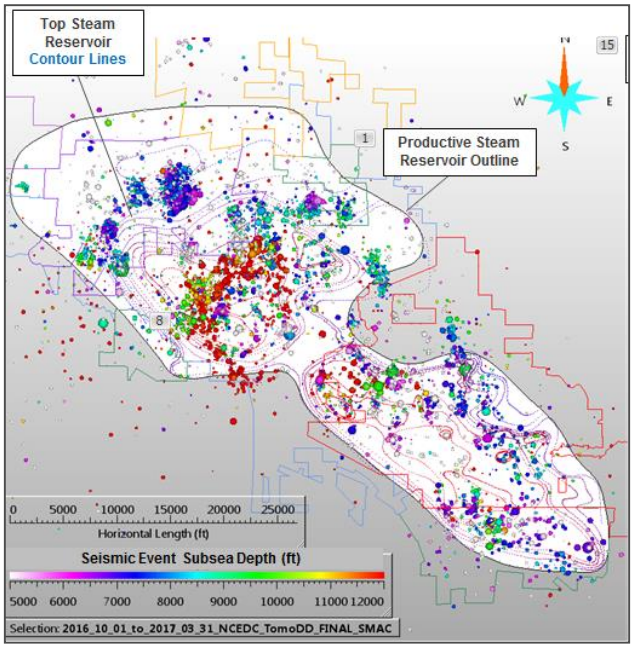
Middletown, California

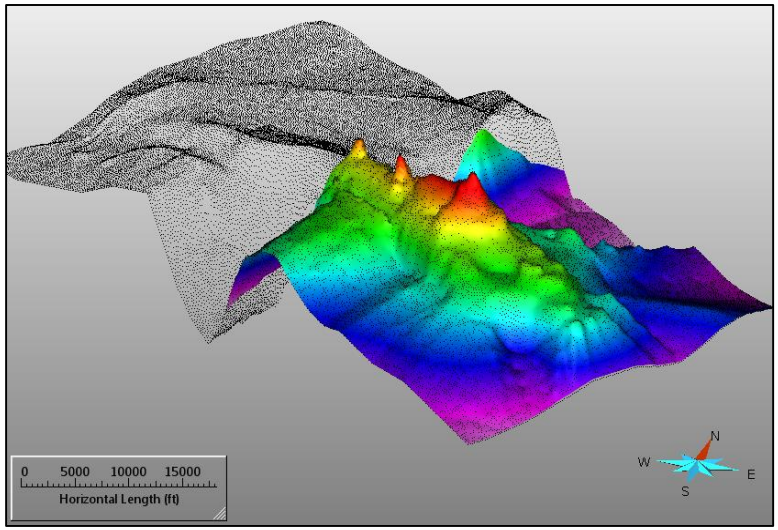
08 May 2017

Craig Hartline Senior Geophysicist Calpine Corporation The Geysers

Seismic Monitoring Advisory Committee Meeting
Calpine Presentation Agenda
Reporting Period: 01 October 2016 to 31 March 2017

- Status of Seismic Monitoring Networks
  - LBNL Seismic Monitoring Network
  - USGS / Northern California Seismic Network
  - Strong Motion Stations
- Fieldwide Seismicity Analysis
- Synchronized Fieldwide Water Injection and Seismicity Analysis
- Community Hotline
- Strong Motion Analysis
- 14 December 2016 Magnitude 5.01 Seismic Event
- Regional Seismicity Analysis
- Water Injection Modifications
- 3D Structural Model Building
- Real-Time Drilling Analysis
- Additional Seismic Monitoring and Research





Status of Seismic Monitoring Networks

LBNL Seismic Monitoring Network - Fully Functional

USGS / Northern California Seismic Network – Fully Functional

Community Strong Motion Stations

- ADS2 Anderson Springs
  This sensor was returned to service by the U.S. Geological Survey and is fully functional.
  The ADS2 database is online at: ftp://ehzftp.wr.usgs.gov/luetgert/calpine/sm_sum.txt

- COB Cobb
  Extreme weather and medical issues delayed LBNL contractor Ramsey Haught's re-installation.
  Will relocate existing LBNL seismic monitoring site ACR to COB site on the Hamilton Hess property.

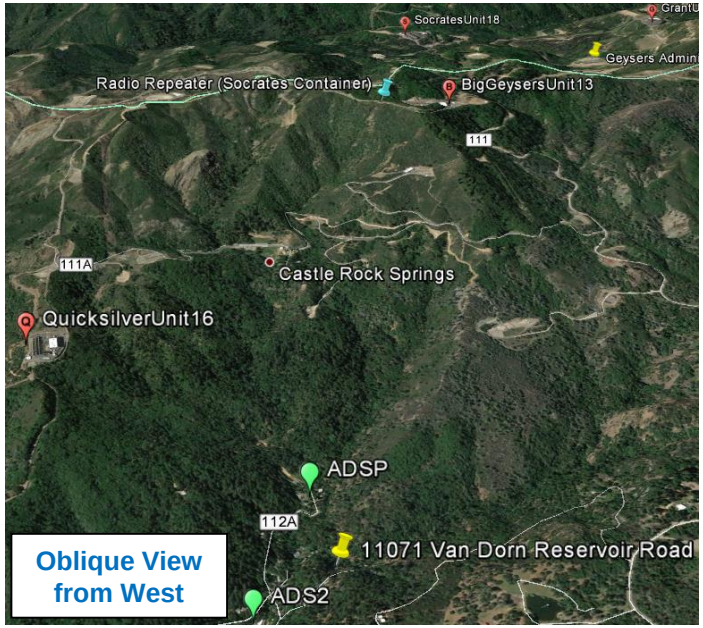
- ADSP Anderson Springs
  Site determination required additional consideration in a community devastated by the Valley Fire.
  Agreed that Anderson Springs community members should assist with site determination.
  Properties of McWilliams, Moulton and Engels were suggested by Jeff Gospe on 19 April 2017.

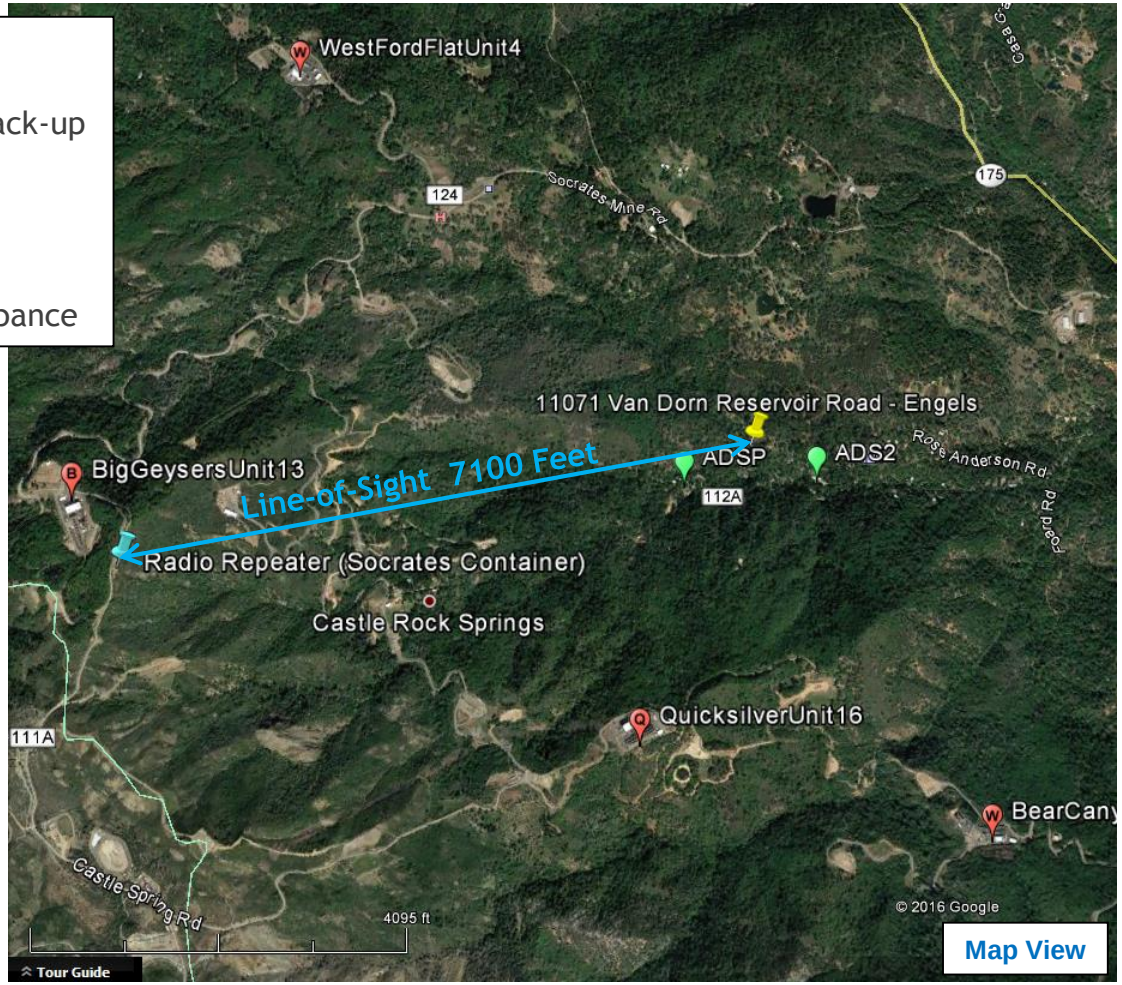
Anderson Springs Community Meeting on 20 April 2017

Cheryl and John Engels offered their property at 11071 Van Dorn Reservoir Road.
Provided access to Calpine's Craig Hartline for a preliminary site evaluation and site photographs.
LBNL contractor Ramsey Haught will next complete a detailed site evaluation.

Site Selection Criteria

- Landowner Approval
- Reliable Solar or AC Power Source / Battery Back-up
- Reliable Radio Telemetry Communication
- Good Sensor Coupling
- Representative Peak Ground Acceleration
- ADSP Measurement Continuity
- Area of Minimal Near-term / Long-term Disturbance





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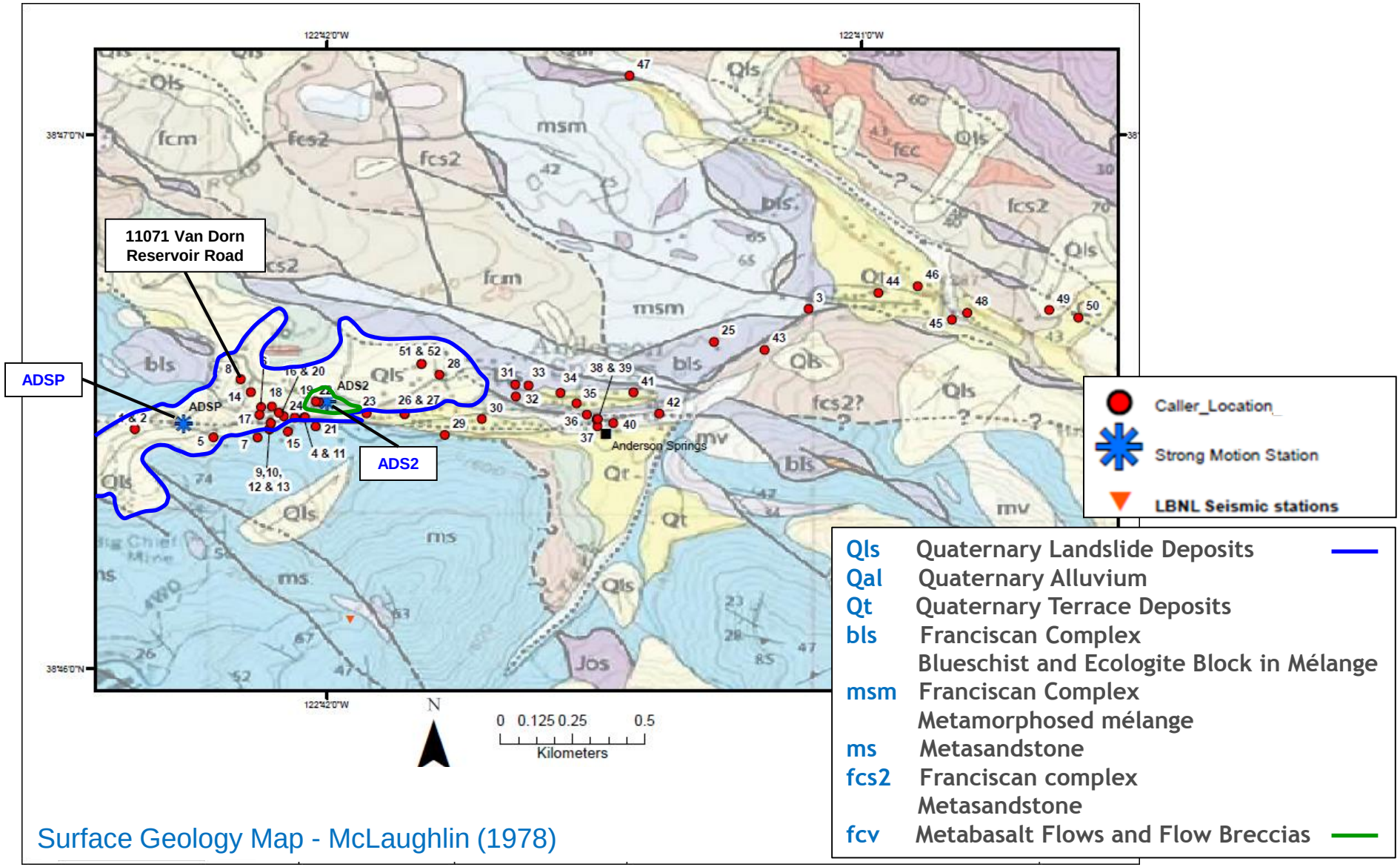
Status of Seismic Monitoring Networks

Anderson Springs Surface Geology and Hotline Caller Locations



Surface Geology Map - McLaughlin (1978)

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Status of Seismic Monitoring Networks

Anderson Springs Surface Geology and Hotline Caller Locations

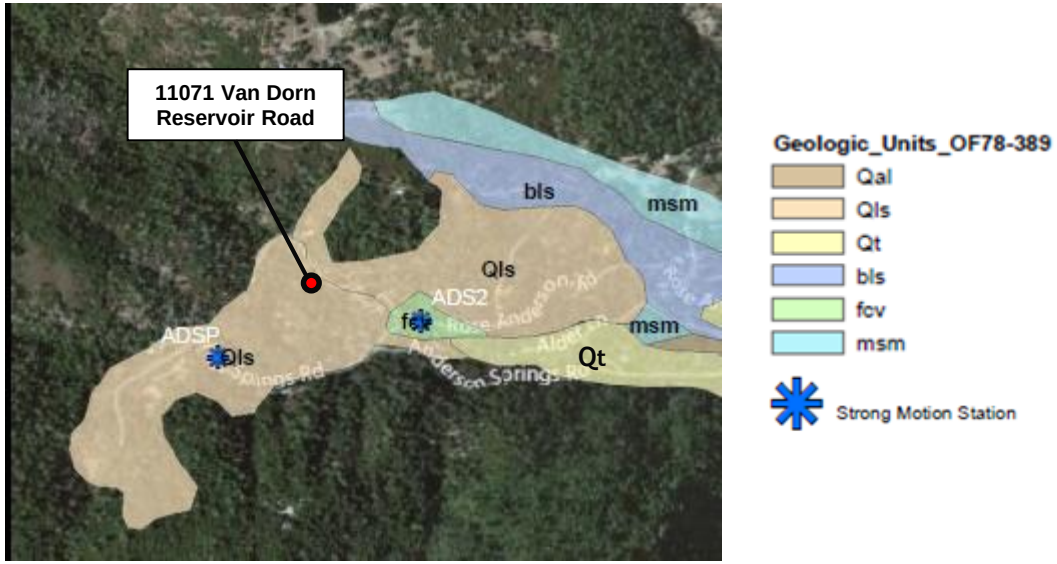
The majority of the hotline callers have their residences on Qls landslide deposits* at the western end of the community.

ADSP site: Qls landslide deposits

relatively thin soil overlying rock
lower shear-wave velocities
this leads to site amplification at short-to-moderate periods (moderate to high frequencies)
this is consistent with relatively high peak ground acceleration values at ADSP

ADS2 site: fcv metabasalt

ground motions recorded on ADS2 are generally lower than ADSP
this is consistent with the observation of site amplification at ADSP due to Qls landslide deposits



** Qls = Quaternary landslide deposits*
The Quaternary period begins at the onset of Northern Hemisphere glaciation about 2.6 million years ago

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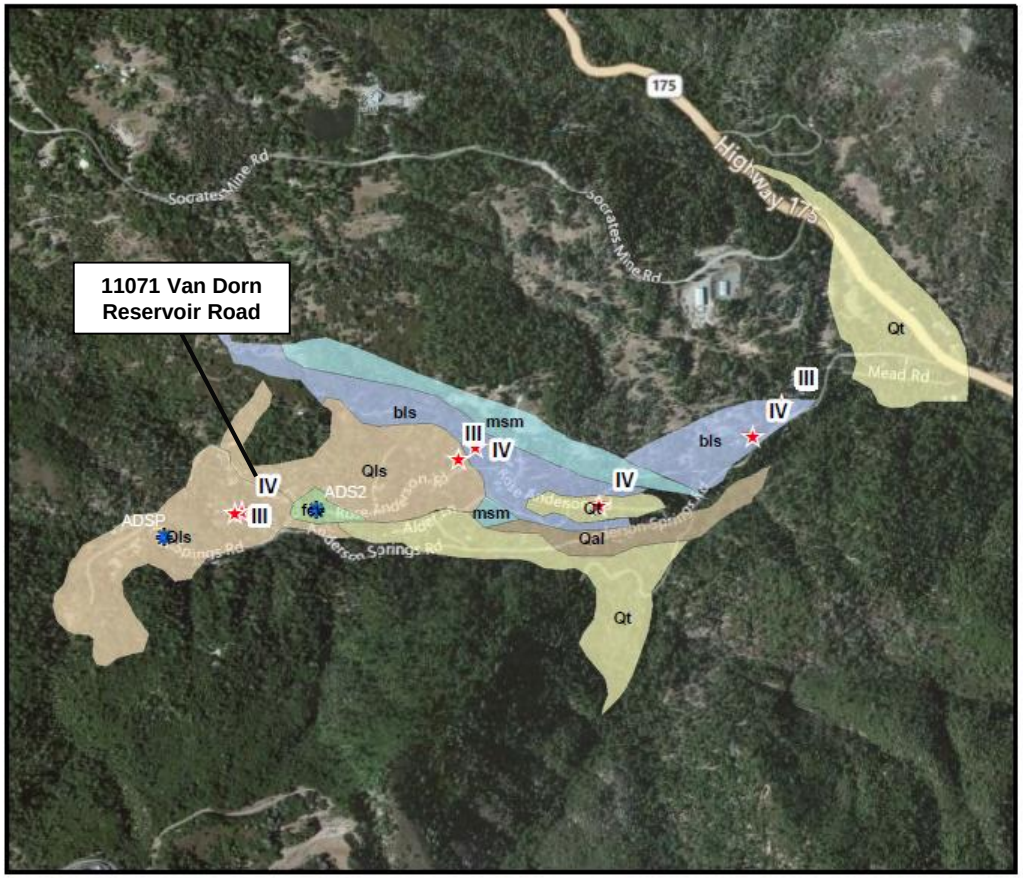
Status of Seismic Monitoring Networks

Anderson Springs Surface Geology and Hotline Caller Locations

Magnitude 3.0 Seismic Event on 14 November 2005



Closest Distance to Felt Report = 1.9 km

ADSP = 0.050 g
COB = 0.028 g

Geologic_Units_OF78-389

- Qal
- Qls
- Qt
- bls
- fcv
- msm

Strong Motion Station

INTENSITY REPORT

V MM Intensity
No Intensity could be estimated.

N

0 0.15 0.3 0.6
Kilometers

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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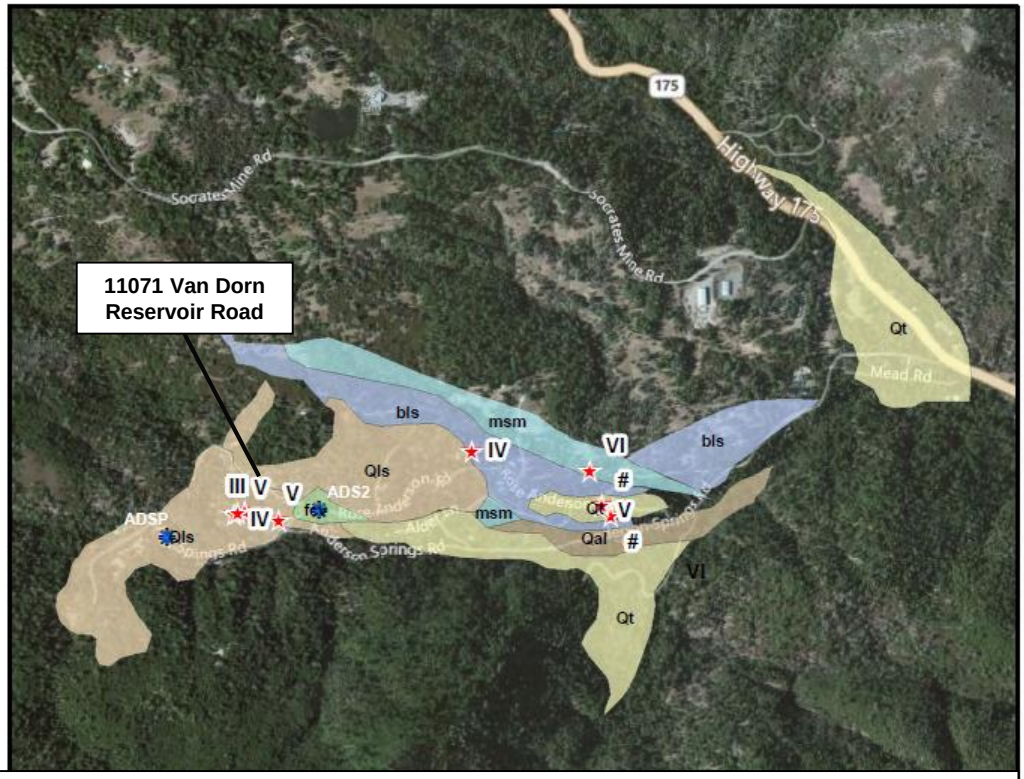
Status of Seismic Monitoring Networks

Anderson Springs Surface Geology and Hotline Caller Locations

Magnitude 4.4 Seismic Event on 09 May 2005



Closest Distance to Felt Report = 1.3 km

ADSP = 0.106 g
COB = 0.086 g

Geologic_Units_OF78-389

- Qal
- Qls
- Qt
- bls
- fcv
- msm

Strong Motion Station

INTENSITY REPORT

V MM Intensity
No Intensity could be estimated.

N

0 0.2 0.4 0.8
Kilometers

The observed shaking at the proposed site is:

- **Consistently equal to or greater than the neighboring observations as indicated by the determined Modified Mercalli Intensity.**
- **Representative of the western end of Anderson Springs and Qls surface geology.**

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
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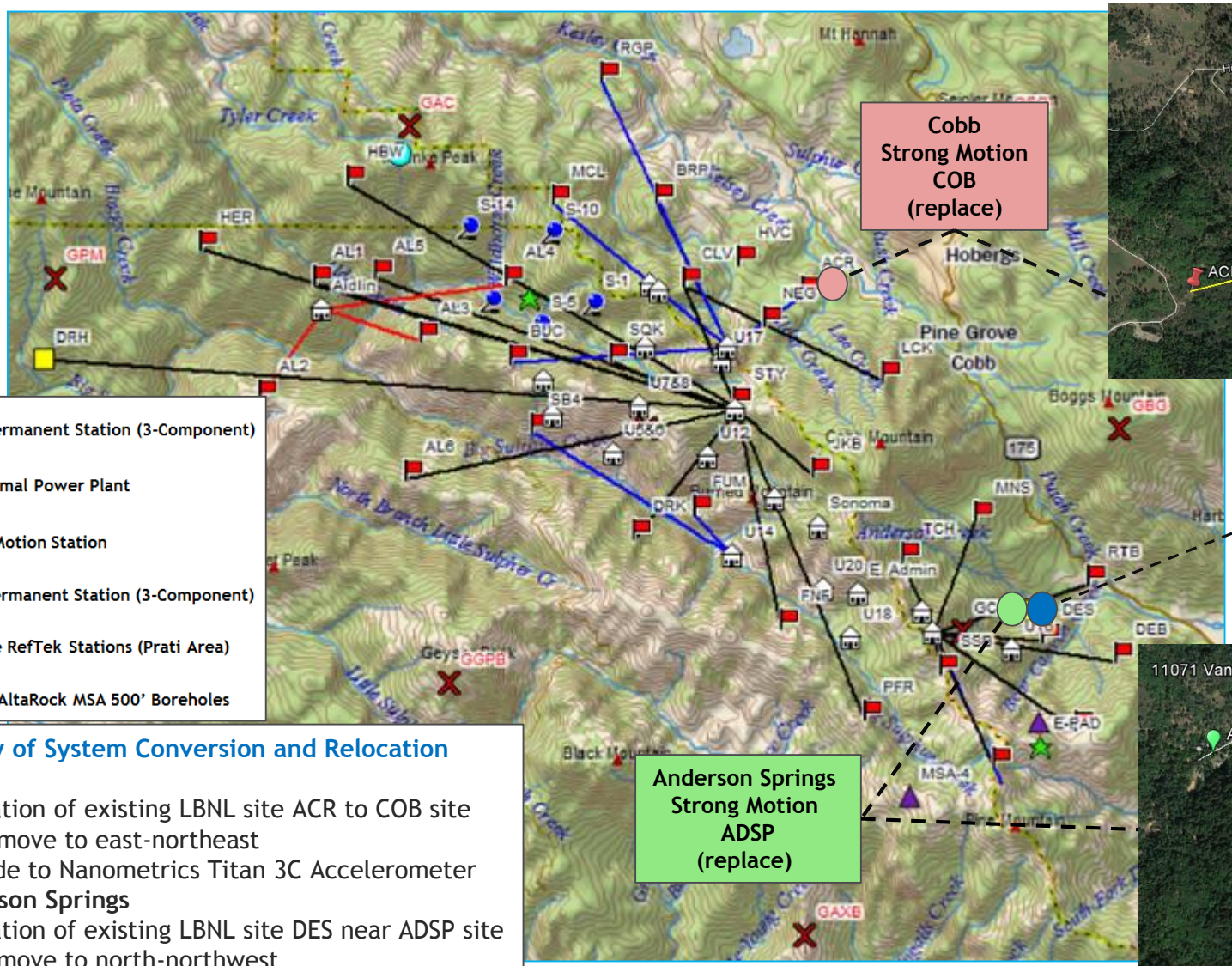
Modified Mercalli Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X

Seismic Monitoring Advisory Committee Meeting

Status of Seismic Monitoring Networks

Integration of Nanometrics Titan Accelerometers into LBNL Network



Summary of System Conversion and Relocation

- ❑ **Cobb**
  Relocation of existing LBNL site ACR to COB site
  2000' move to east-northeast
  Upgrade to Nanometrics Titan 3C Accelerometer
- ❑ **Anderson Springs**
  Relocation of existing LBNL site DES near ADSP site
  2800' move to north-northwest
  Upgrade to Nanometrics Titan 3C Accelerometer

Status of Seismic Monitoring Networks
Nanometrics Titan Accelerometers Specifications

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 μg/°C, typical Vertical sensor: 320 μg/°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 XYZ 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

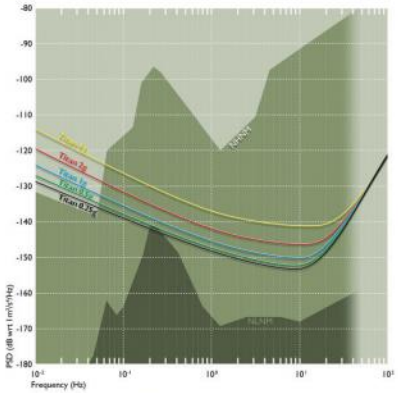
Hardware Interface

Connectors	MIL-C-26482G Series 1, 14-pin, shell size 12
Acceleration Output	40 Vpp differential
Output Impedance	2 x 100 Ω
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

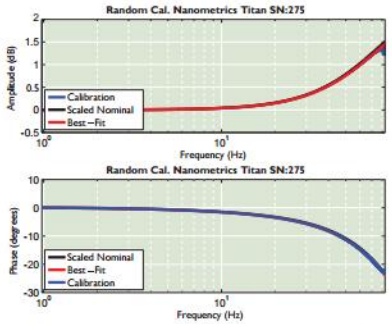
Power

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
250 Herzberg Road, Kanata, Ontario, Canada, K2K 2A1
613-592-6776 | Fax: 613-592-5929
www.nanometrics.ca | info@nanometrics.ca

Document #: 1002.15.01 Printed in Canada

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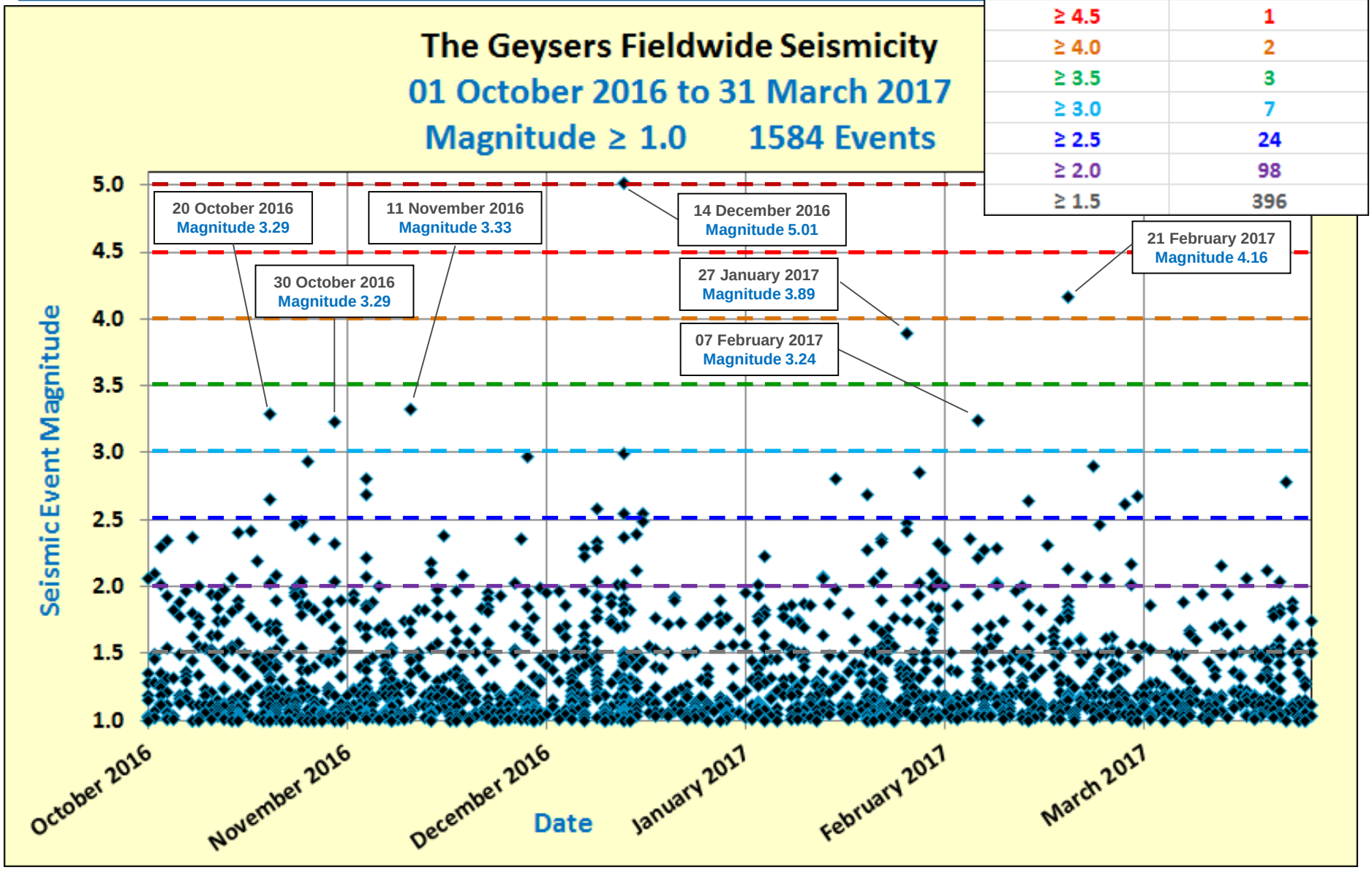
Field-wide Seismicity Analysis
01 October 2016 to 31 March 2017

Magnitude	Number of Events
≥ 5.0	1
≥ 4.5	1
≥ 4.0	2
≥ 3.5	3
≥ 3.0	7
≥ 2.5	24
≥ 2.0	98
≥ 1.5	396



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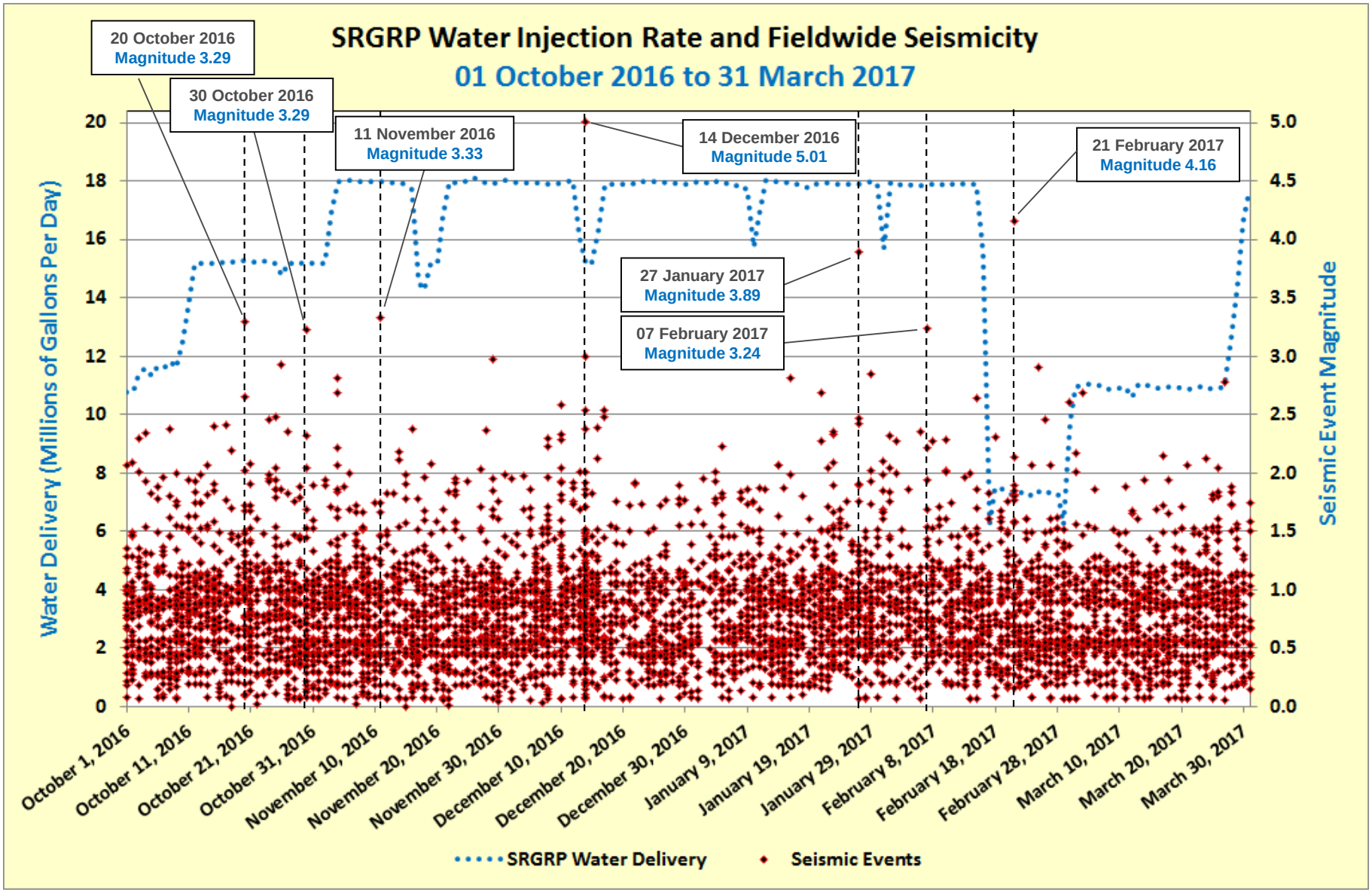
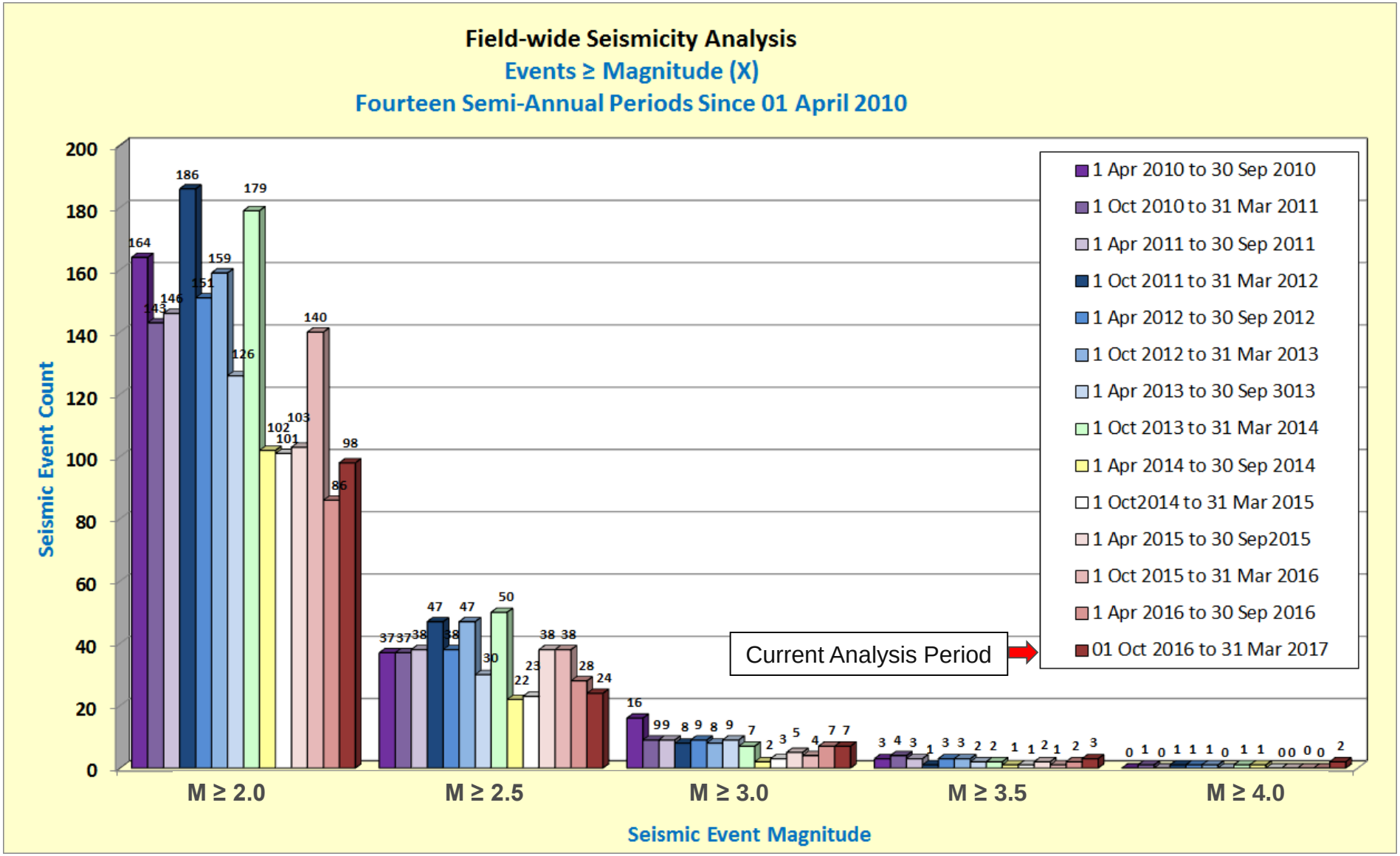
SRGRP Water Injection Rate and Fieldwide Seismicity
01 October 2016 to 31 March 2017

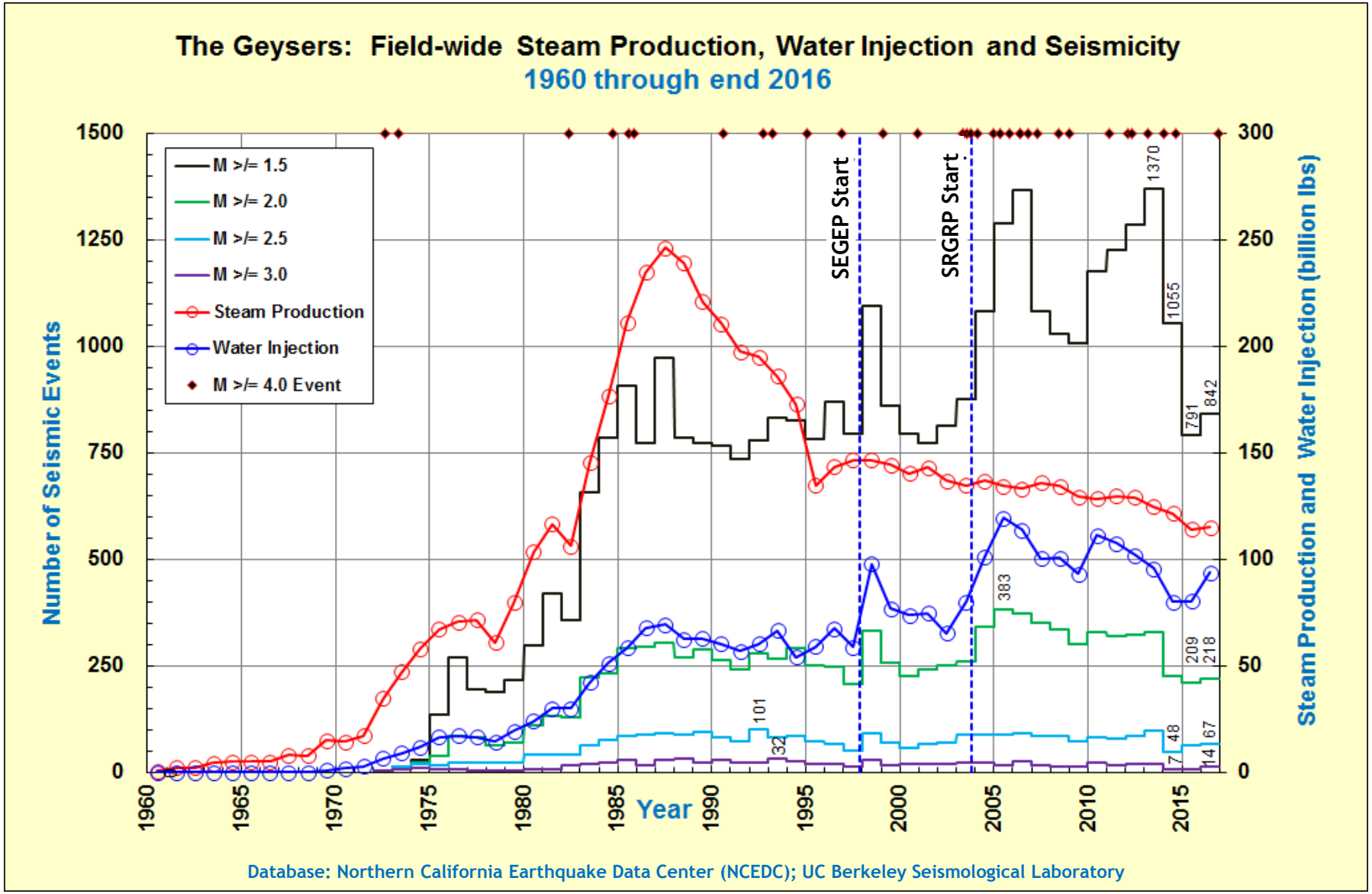


Seismic Monitoring Advisory Committee Meeting

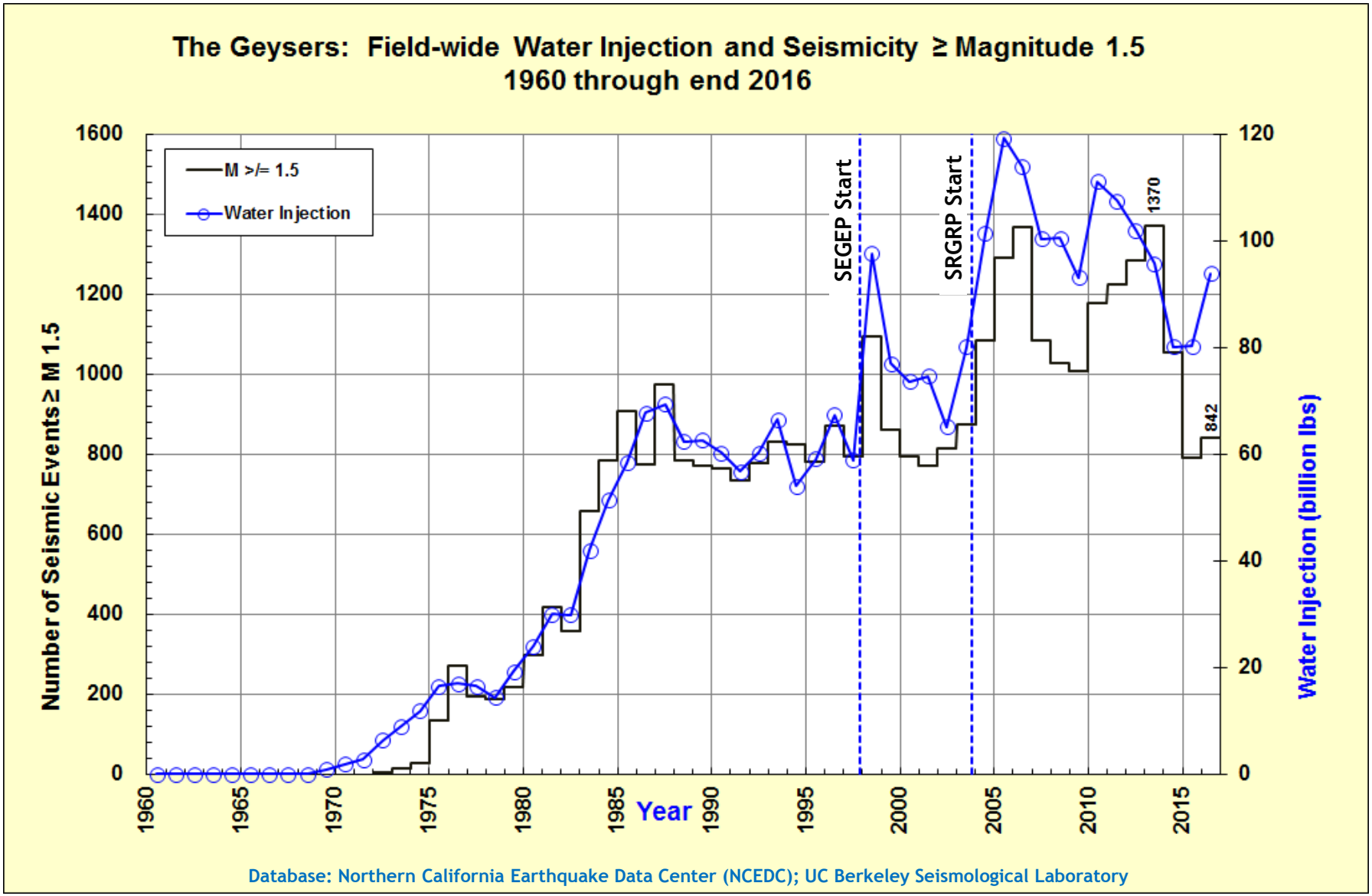
Field-wide Seismicity Analysis
Comparison of Fourteen Semi-annual Reporting Periods



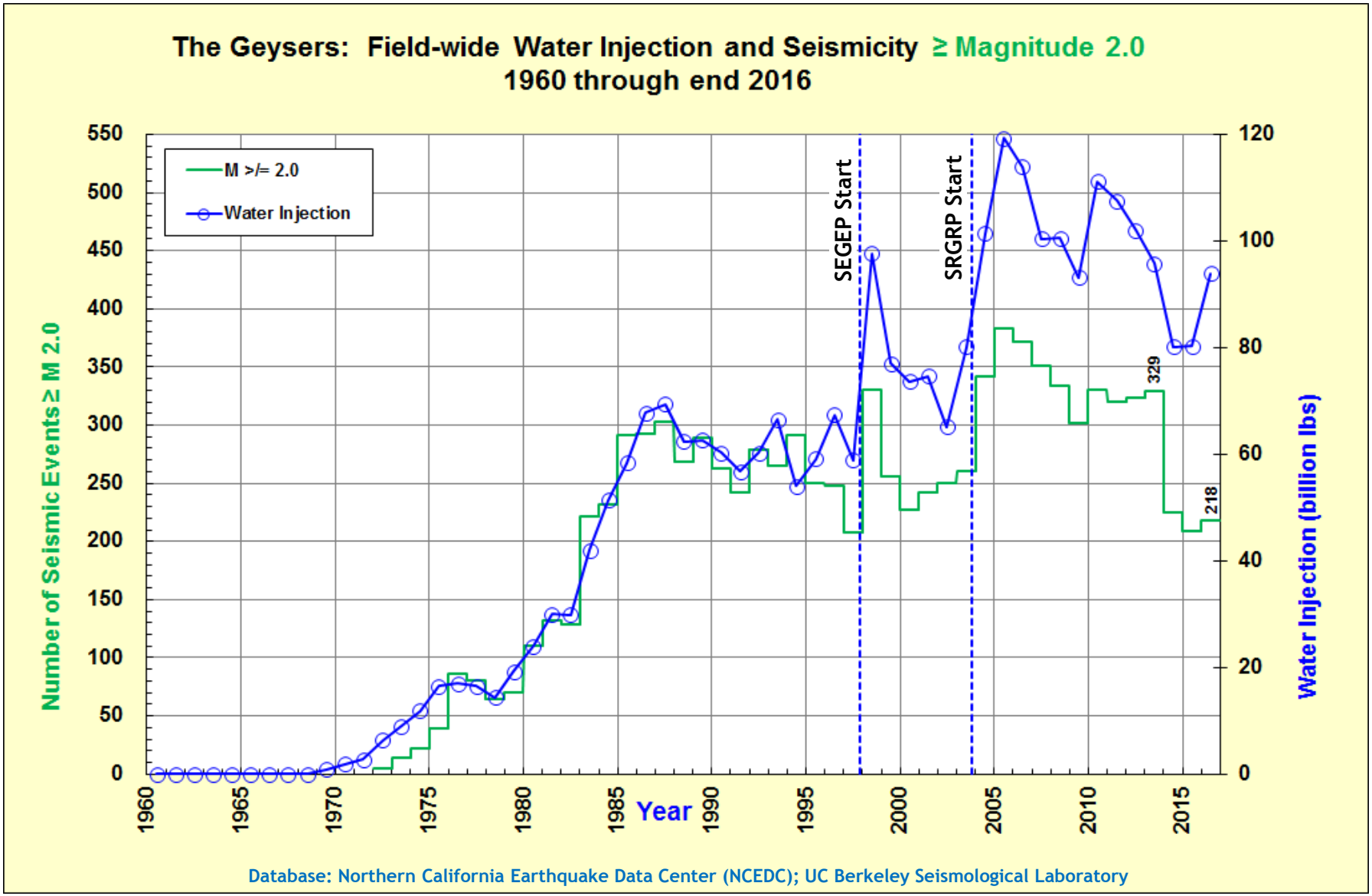
Yearly Field-wide Steam Production, Water Injection and Seismicity



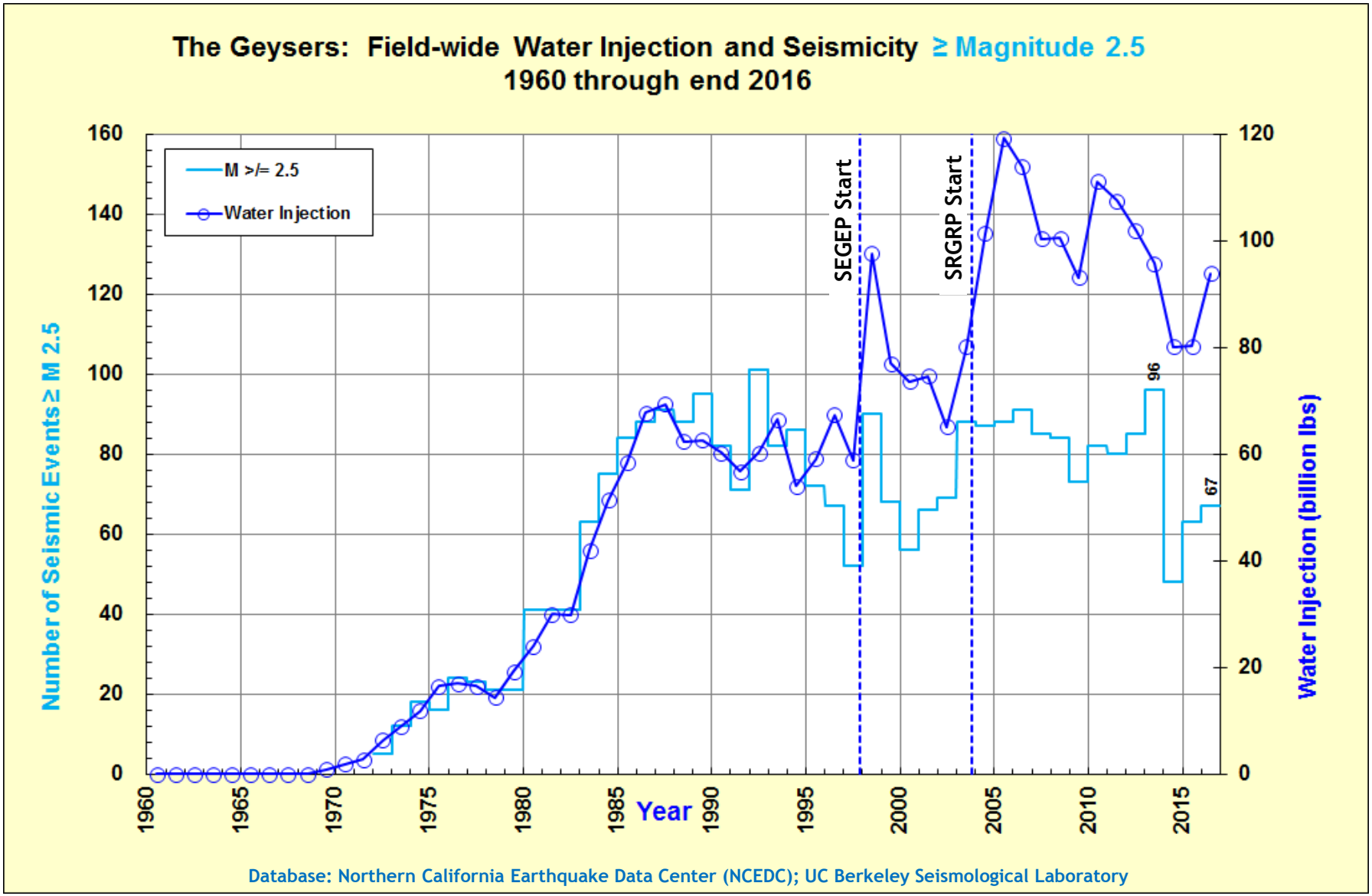
Yearly Field-wide Water Injection and Magnitude ≥ 1.5 Seismicity



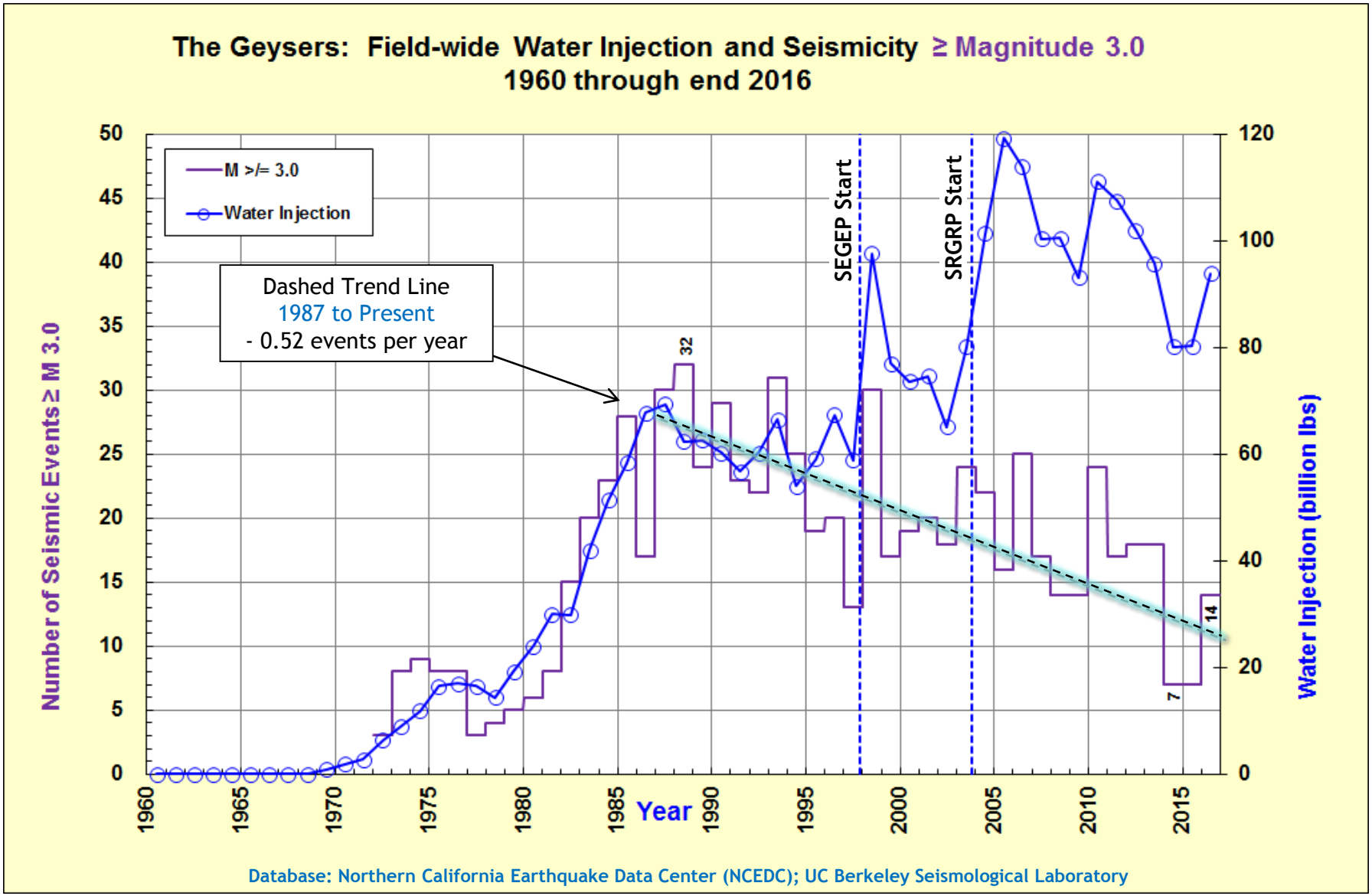
Yearly Field-wide Water Injection and Magnitude ≥ 2.0 Seismicity



Yearly Field-wide Water Injection and Magnitude ≥ 2.5 Seismicity



Yearly Field-wide Water Injection and Magnitude ≥ 3.0 Seismicity



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Monthly Field-wide Water Injection vs. Magnitude ≥ 4.0 Seismicity

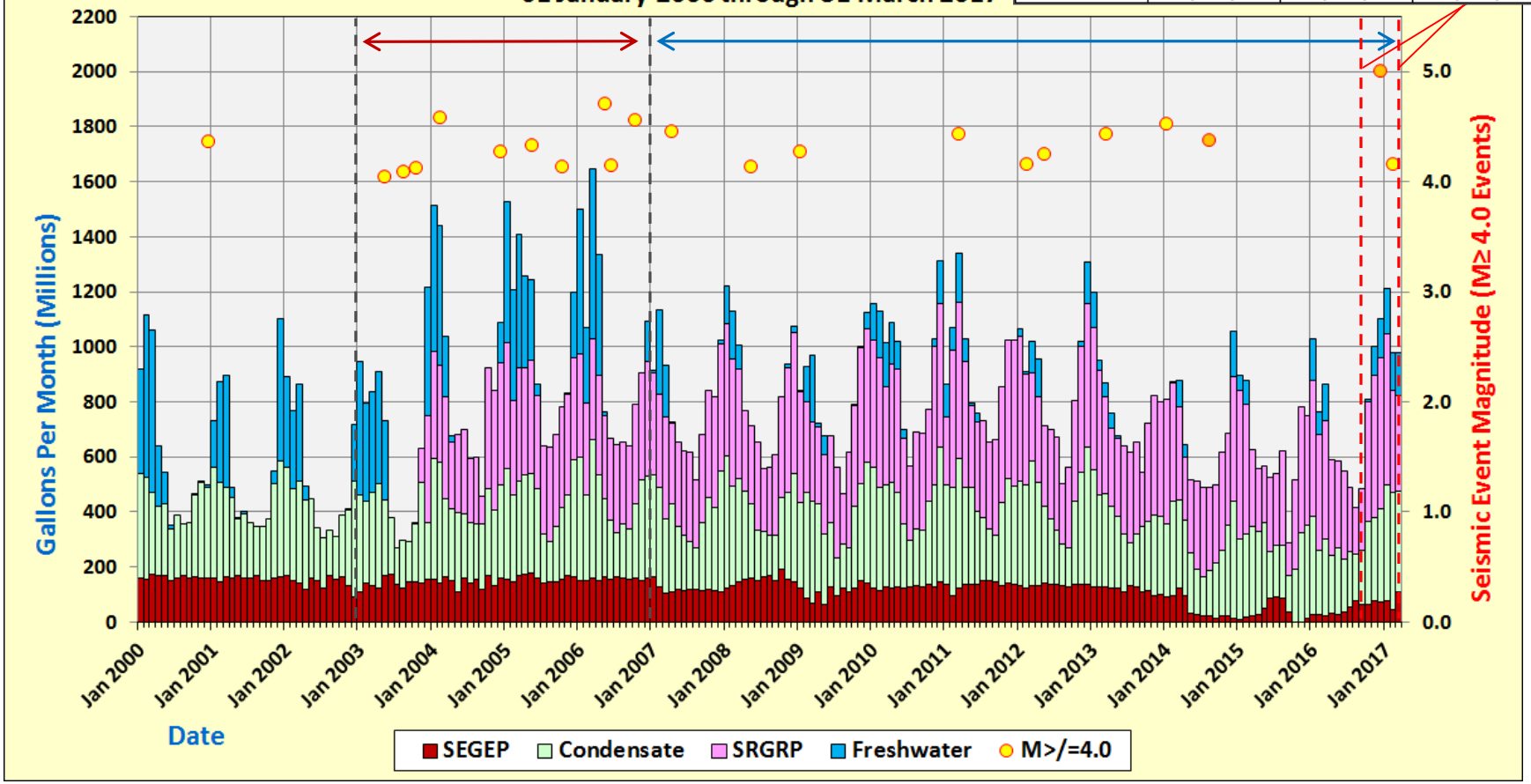
Average Number of Magnitude ≥ 4.0 Events Per Year Significantly Less Than 2003-2006 Peak

Time Period	Magnitude ≥ 4.0 Seismic Events
January 2003 through December 2006	2.50 per year
January 2007 through March 2017	1.07 per year

Water Supply for Reporting Period (Six Months)

Water Injection Sources (Gallons)

Month	SEGEP	SRGRP	Condensate	Fresh Water
October	62,432,000	432,400,000	304,725,053	7,259,657
November	77,695,000	518,440,000	299,872,170	103,066,295
December	72,371,000	546,900,000	340,737,099	140,435,129
January	76,953,000	549,700,000	421,678,860	163,211,893
February	43,053,000	370,760,000	425,896,401	140,383,159
March	108,071,000	350,470,000	365,801,329	154,334,105



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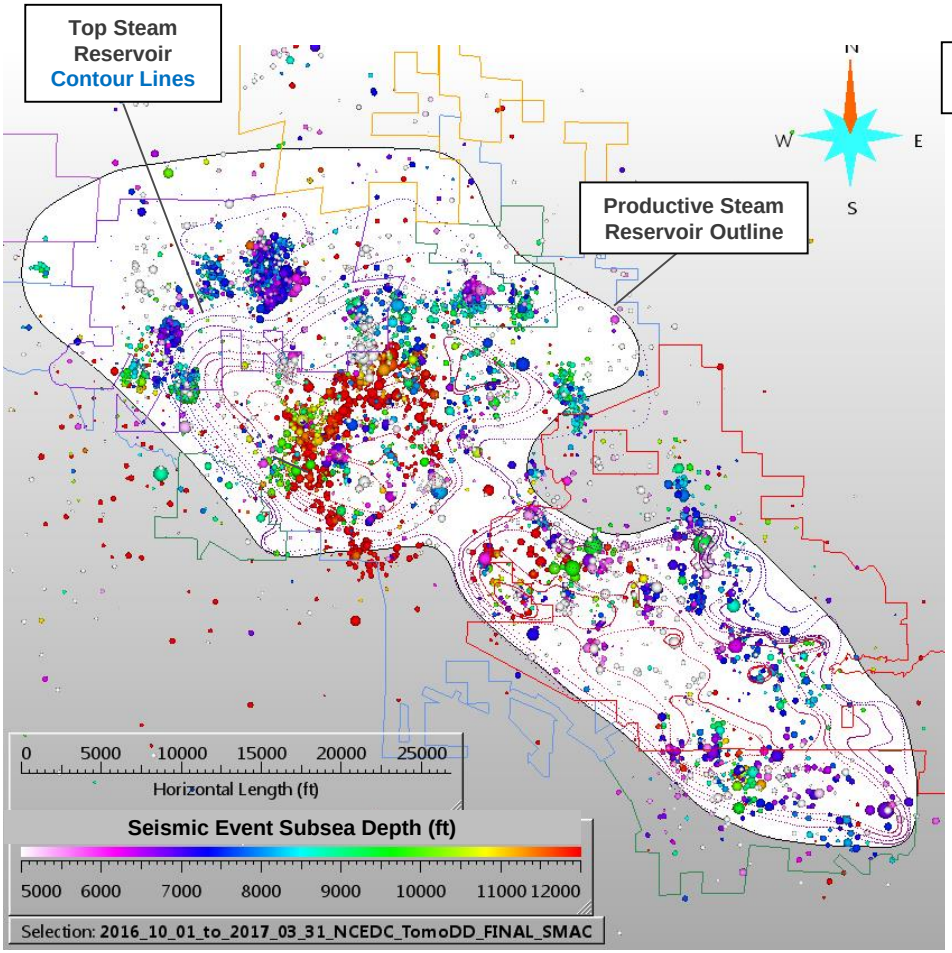
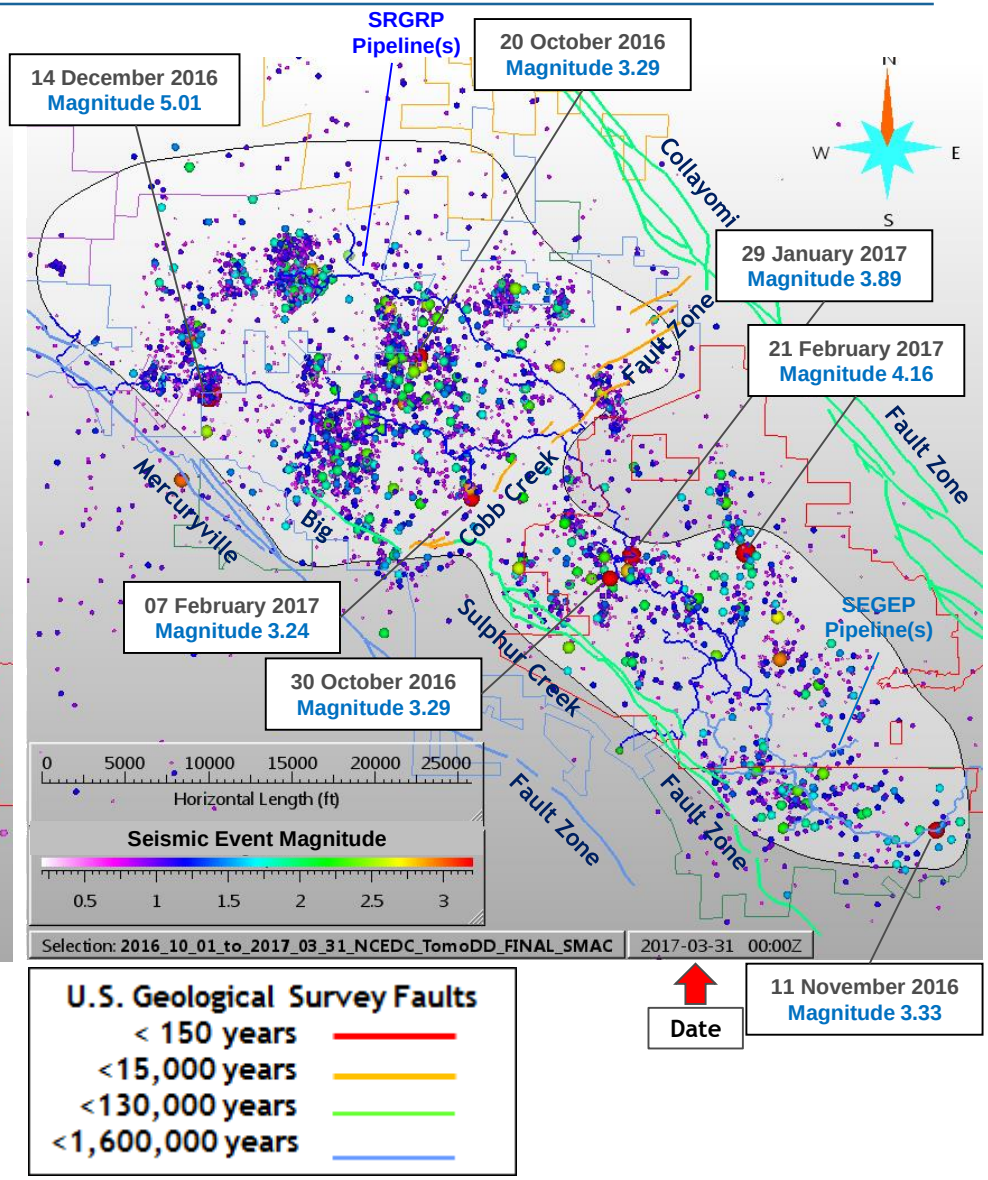
Fieldwide Induced Seismicity Animation

01 October 2016 to 31 March 2017





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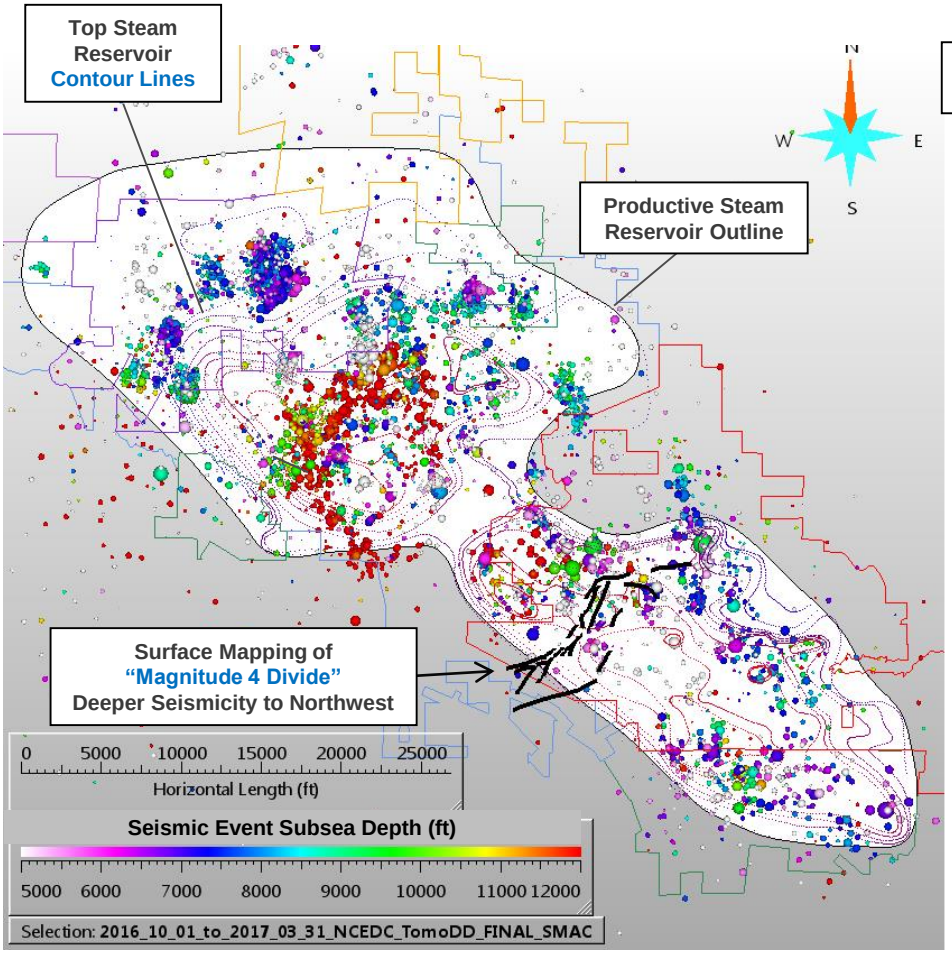
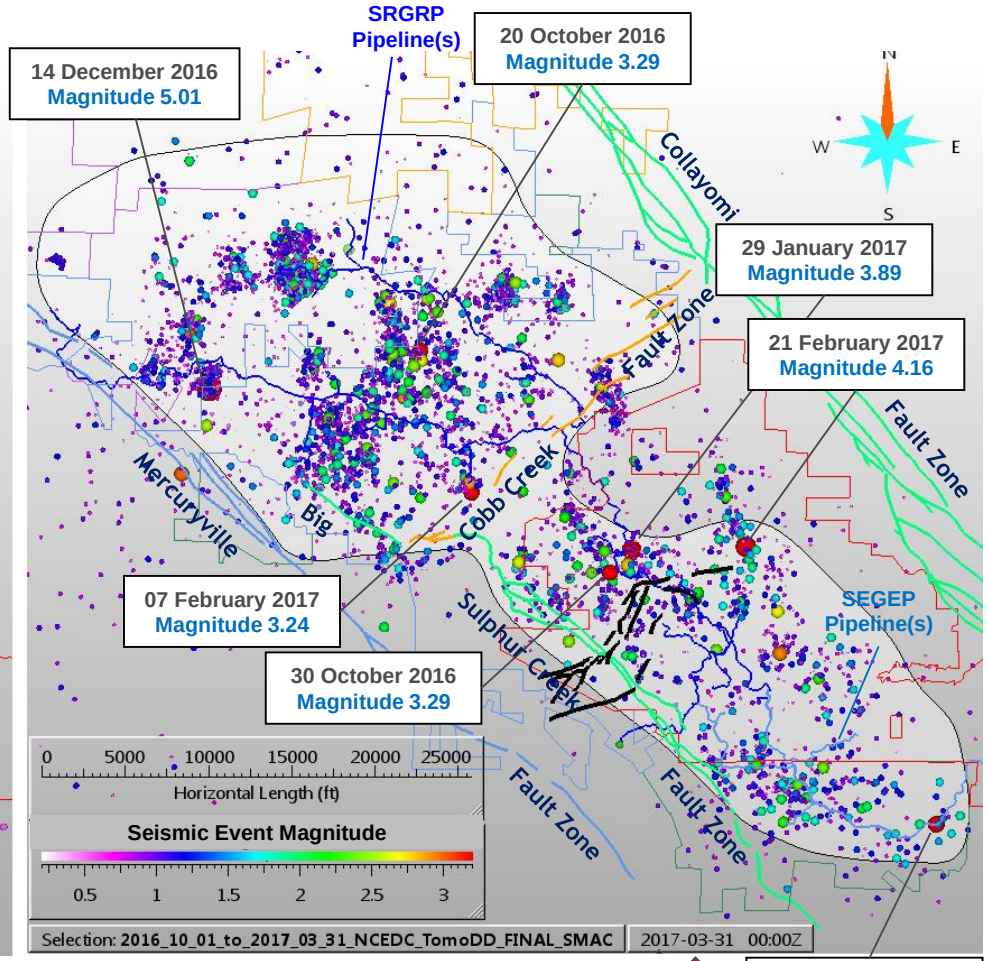
Fieldwide Induced Seismicity Animation

01 October 2016 to 31 March 2017





U.S. Geological Survey Faults

- < 150 years
- <15,000 years
- <130,000 years
- <1,600,000 years

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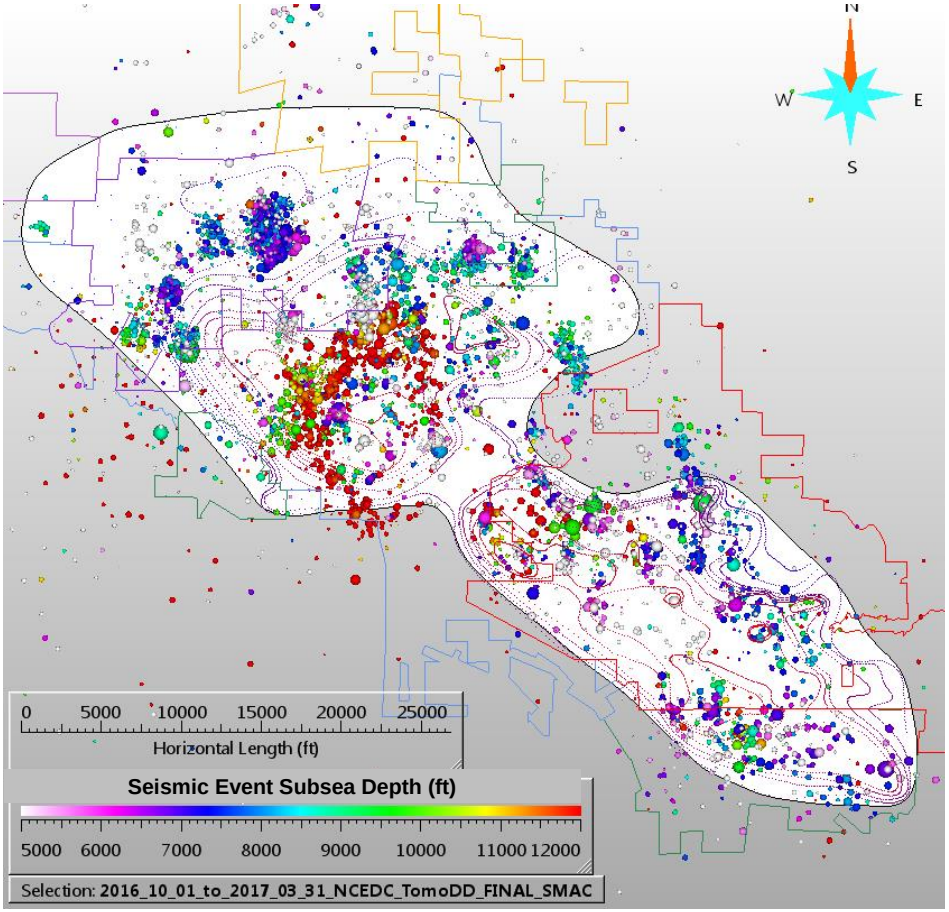
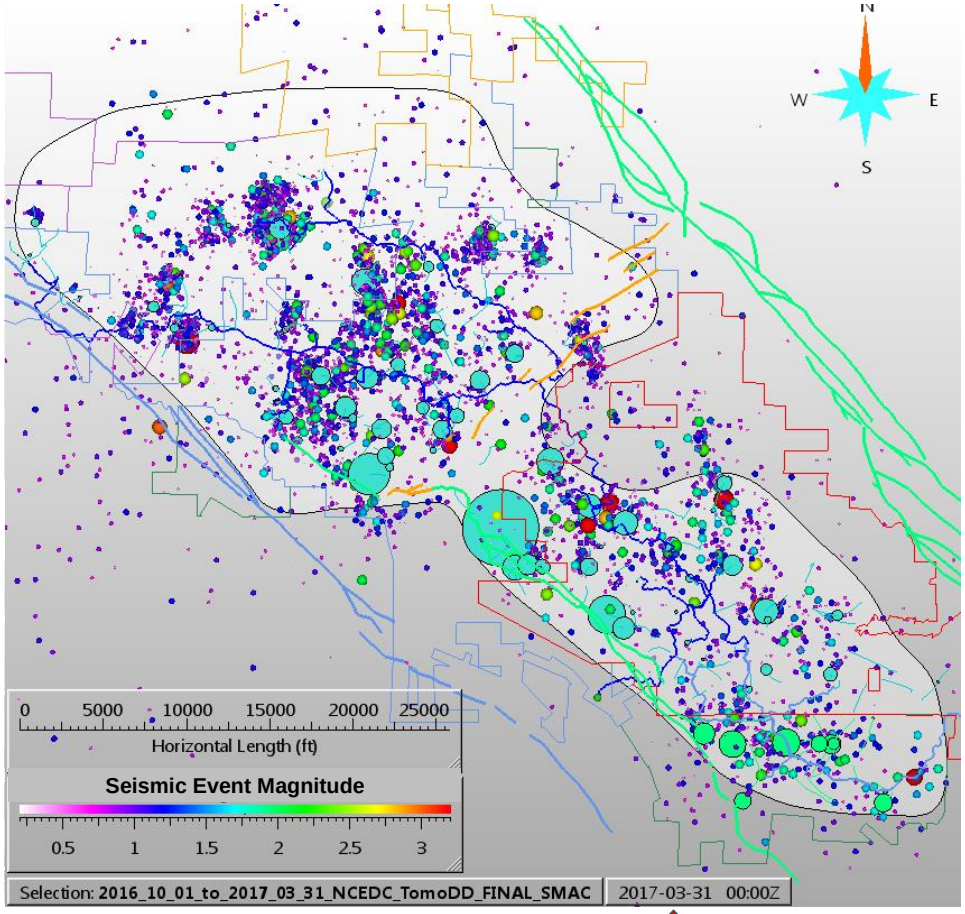
Fieldwide Water Injection and Induced Seismicity Animation
01 October 2016 to 31 March 2017





Date

Monthly Water Injection Volume
All Historical Injection Wells
Equivalent to Blue/Green Disc Radius

U.S. Geological Survey Faults
< 150 years
<15,000 years
<130,000 years
<1,600,000 years

Calpine Seismicity Hotline

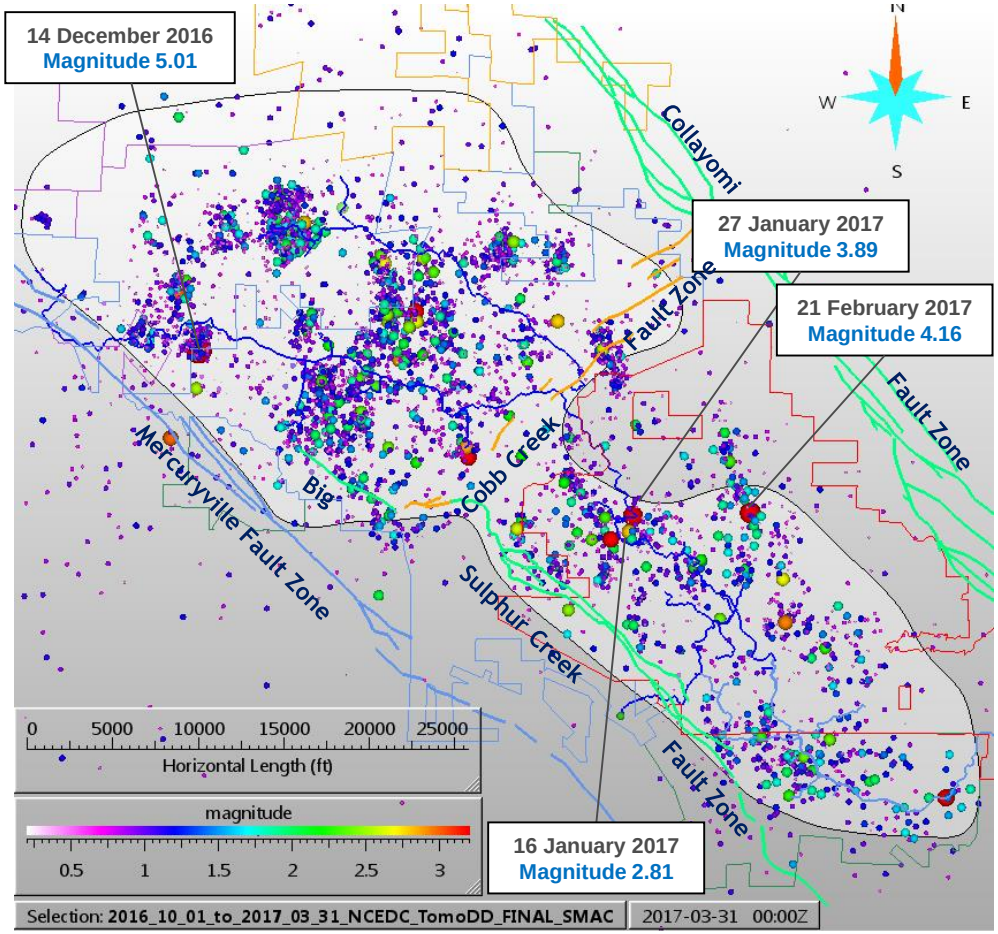
The communities are understandably focused on efforts to recover from the Valley Fire, resulting in only a total of seven calls, all from Anderson Springs, to the Calpine Community Hotline during the current reporting period of 01 October 2016 to 31 March 2017. The events responsible for calls were:

Magnitude 5.01 Seismic Event (four calls)
Date and Time: 14 December 2016 at 16:41:06 UTC
Latitude: North 38.82217
Longitude: West 122.84133
Depth: 4855 feet (1.48 km) Below Sea Level

Magnitude 2.81 Seismic Event (one call)
Date and Time: 16 January 2017 at 13:35:45 UTC
Latitude: North 38.79250
Longitude: West 122.73733
Depth: 4120 feet (1.28 km) Below Sea Level

Magnitude 3.89 Seismic Event (one call)
Date and Time: 27 January 2017 at 19:08:30 UTC
Latitude: North 38.79350
Longitude: West 122.75616
Depth: 8825 feet (2.69 km) Below Sea Level

Magnitude 4.16 Seismic Event (one call)
Date and Time: 21 February 2017 at 00:57:53 UTC
Latitude: North 38.79583
Longitude: West 122.73534
Depth: 4330 feet (1.32 km) Below Sea Level



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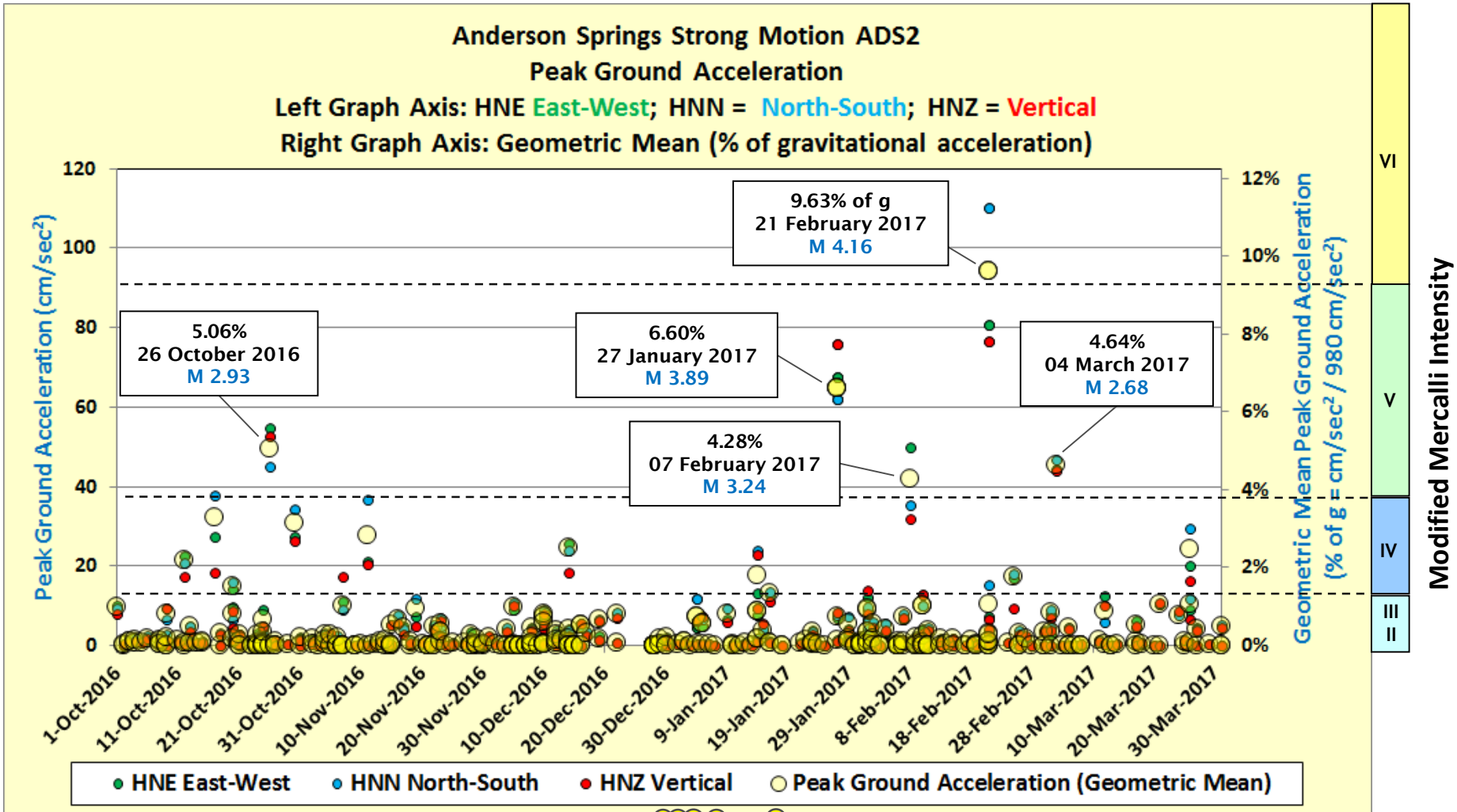
Anderson Springs Strong Motion Station ADS2



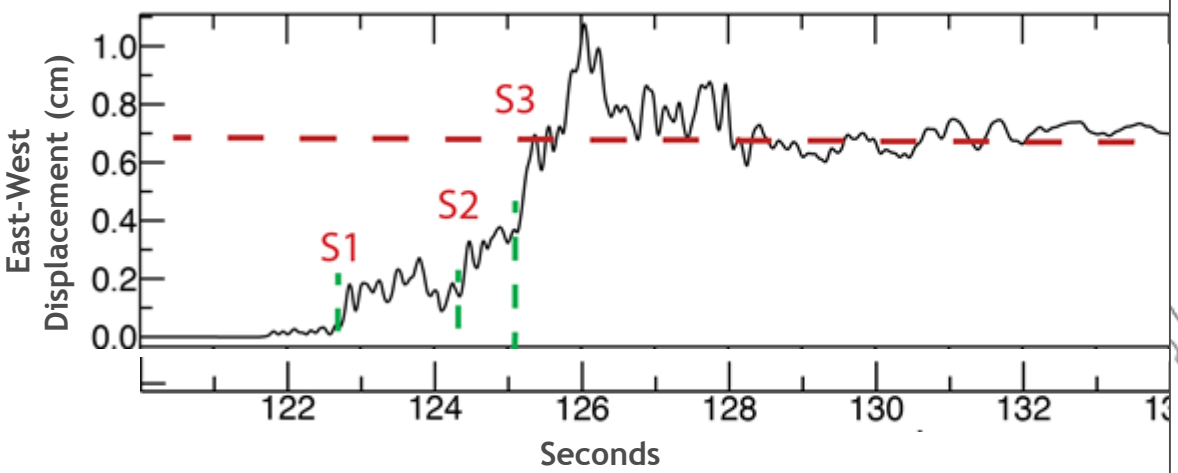
Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	None	None	None	Very Light	Light	Moderate	Mod/Heavy	Heavy	Very Heavy
Peak Acceleration (% of g)	< 0.17	0.17 - 1.4	1.4 - 3.9	3.9 - 9.2	9.2 - 18.0	18.0 - 34.0	34.0 - 65.0	65.0 - 124.0	> 124.0
Peak Velocity (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

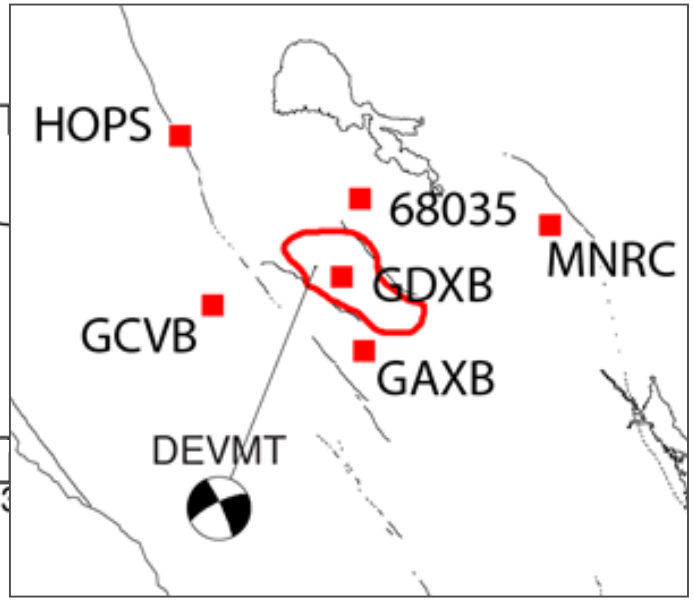
Seismic Monitoring Advisory Committee Meeting
14 December 2016 Magnitude 5.01 Seismic Event

Dr. Doug Dreger of the Berkeley Seismological Laboratory has completed a *preliminary* Moment Tensor* analysis to determine the Seismic Moment of the 14 December 2016 magnitude 5.01 seismic event.

Seismic Moment:
A measure of the size of an earthquake based on the area of fault rupture, average slip, and rock rigidity.

The mathematical analysis of the closest strong-motion station (GDXB) indicates a complex slip distribution with at least three discrete aligned shear motions (S1, S2 and S3).





- **Moment Tensor**:
  A mathematical representation of the movement on a fault during an earthquake, comprising nine sets coupled vectors.

14 December 2016 Magnitude 5.01 Seismic Event

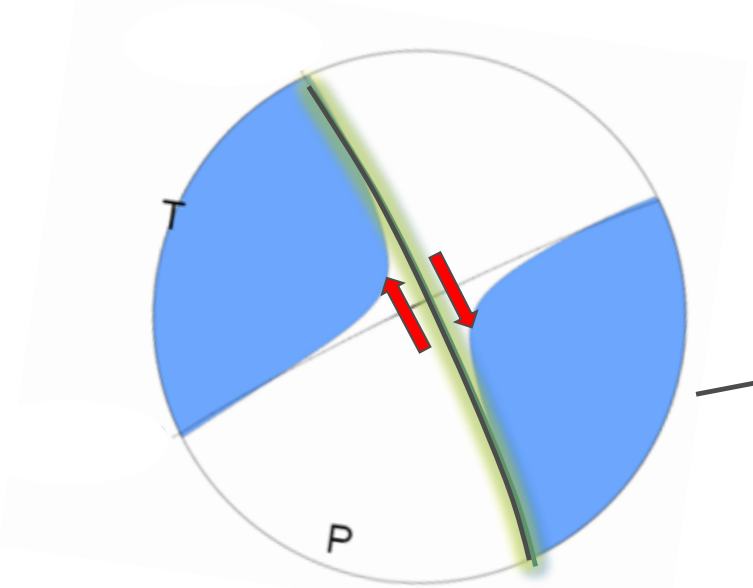
The ***preliminary*** **Moment Tensor** analysis also concluded:

- Magnitude 5.01
- Depth 1.5 km (5000') below sea level.
- Likely rupture surface orientation is north 35° west and nearly vertical (84°).
- Shear motion or double-couple motion; one side of the fault plane sliding directly along the other.
- No statistically significant **volumetric** component.

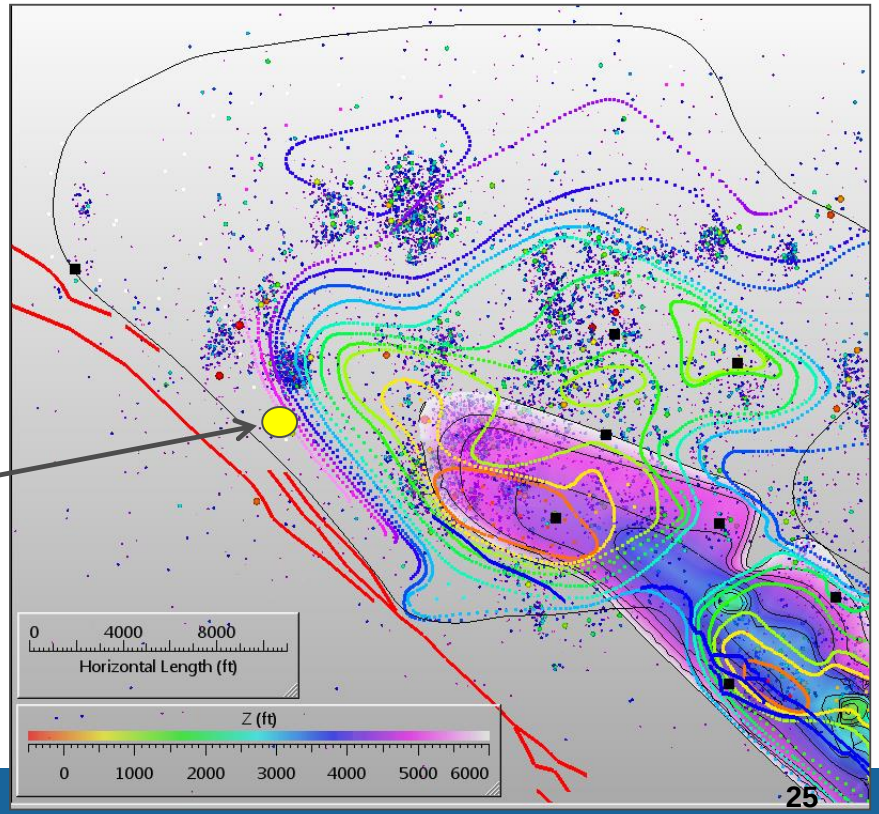
Induced seismic events often include a volumetric component as pressurized fluid opens a fracture

The first motion determined is entirely *consistent* with a naturally occurring earthquake.

- The moment tensor analysis is *consistent* with right-lateral strike-slip motion along the San Andreas Fault System.



tensional and pressure axes labeled



Field-wide Seismicity Analysis

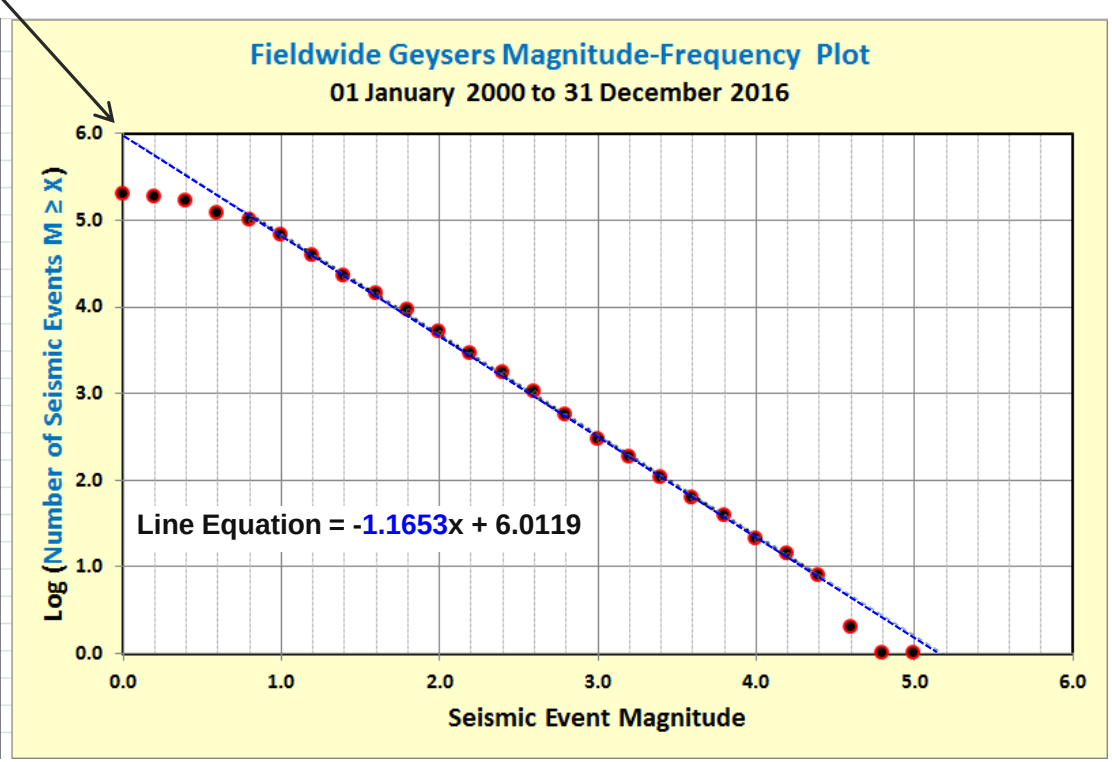
Gutenberg-Richter Analysis (b-values) from January 2000 to Present

The Gutenberg–Richter Law expresses the relationship between the magnitude and total number of earthquakes in a given region.

$\log_{10} N = a - bM$ **N is the number of events ≥ magnitude M**

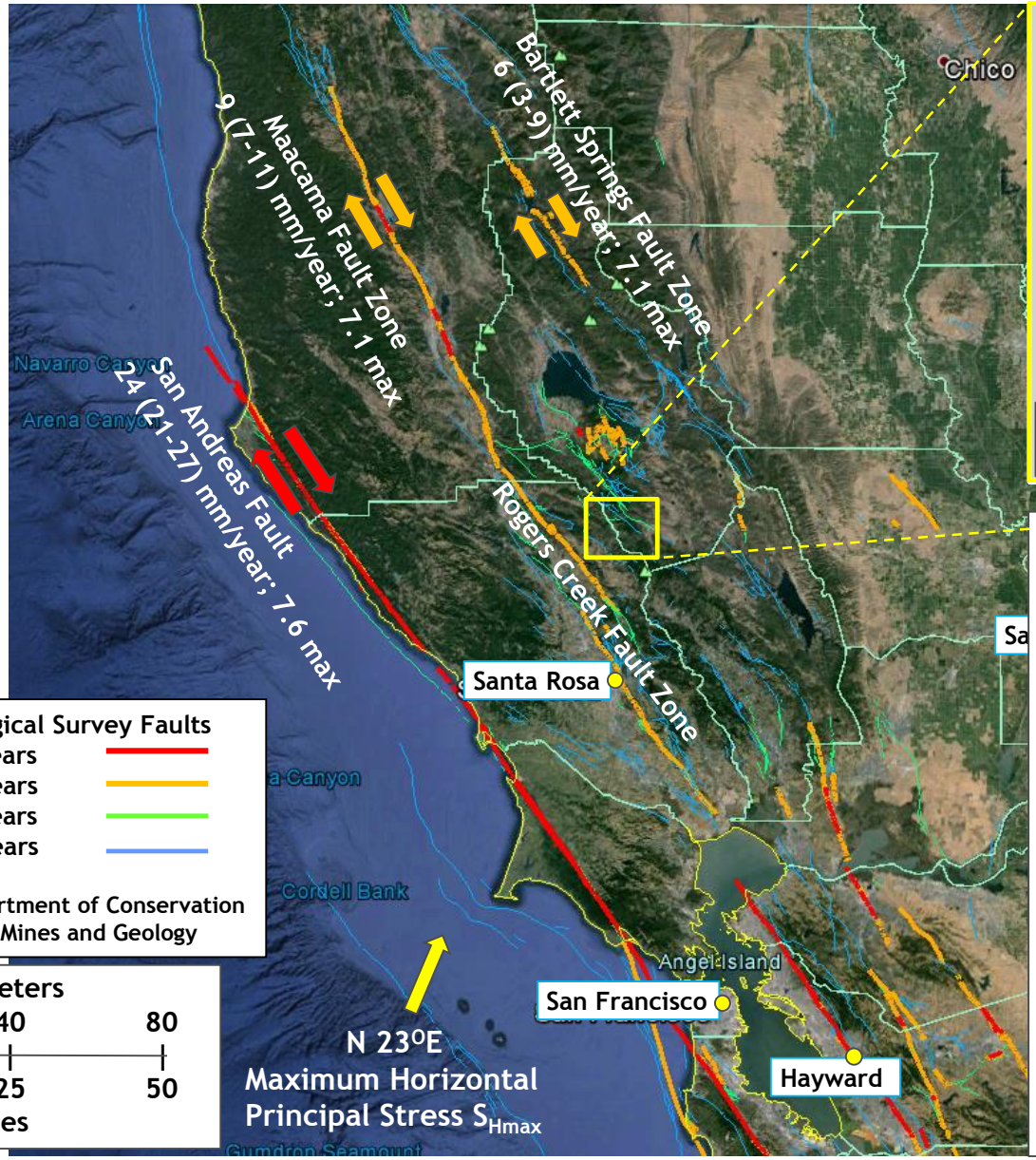
b is the line slope

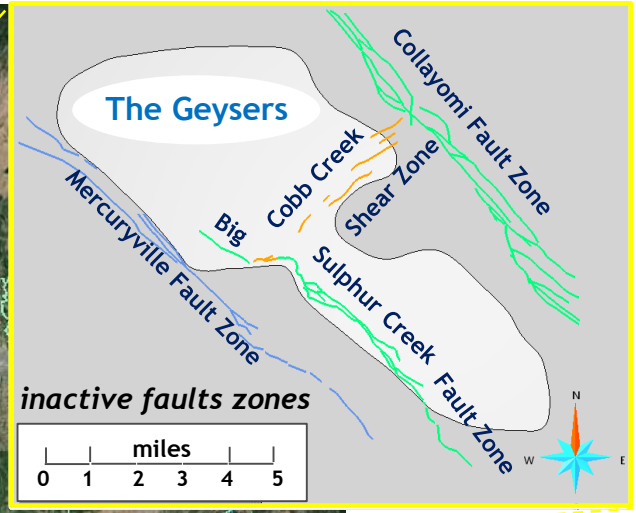
Minimum Magnitude	Maximum Magnitude	# of Events in Range	Cumulative	Log_{10}
0.0	0.2	12483.0	197487	5.30
0.2	0.4	19330.0	185004	5.27
0.4	0.6	46364.0	165674	5.22
0.6	0.8	20539.0	119310	5.08
0.8	1.0	32108.0	98771	4.99
1.0	1.2	28189.0	66663	4.82
1.2	1.4	15464.0	38474	4.59
1.4	1.6	8677.0	23010	4.36
1.6	1.8	5280.0	14333	4.16
1.8	2.0	3891.0	9053	3.96
2.0	2.2	2258.0	5162	3.71
2.2	2.4	1166.0	2904	3.46
2.4	2.6	709.0	1738	3.24
2.6	2.8	460.0	1029	3.01
2.8	3.0	273.0	569	2.76
3.0	3.2	113.0	296	2.47
3.2	3.4	77.0	183	2.26
3.4	3.6	44.0	106	2.03
3.6	3.8	23.0	62	1.79
3.8	4.0	18.0	39	1.59
4.0	4.2	7.0	21	1.32
4.2	4.4	6.0	14	1.15
4.4	4.6	6.0	8	0.90
4.6	4.8	1.0	2	0.30
4.8	5.0	0.0	1	0.00
5.0	5.2	1.0	1	0.00



Seismic Monitoring Advisory Committee Meeting

Regional Geology and Limitations on Seismic Event Magnitude





Seismic event magnitude depends on:

- fault area
- rock rigidity
- slip rate

Within The Geysers, mapped faults are inactive and restricted in area, limiting the maximum possible seismic event magnitude and duration.

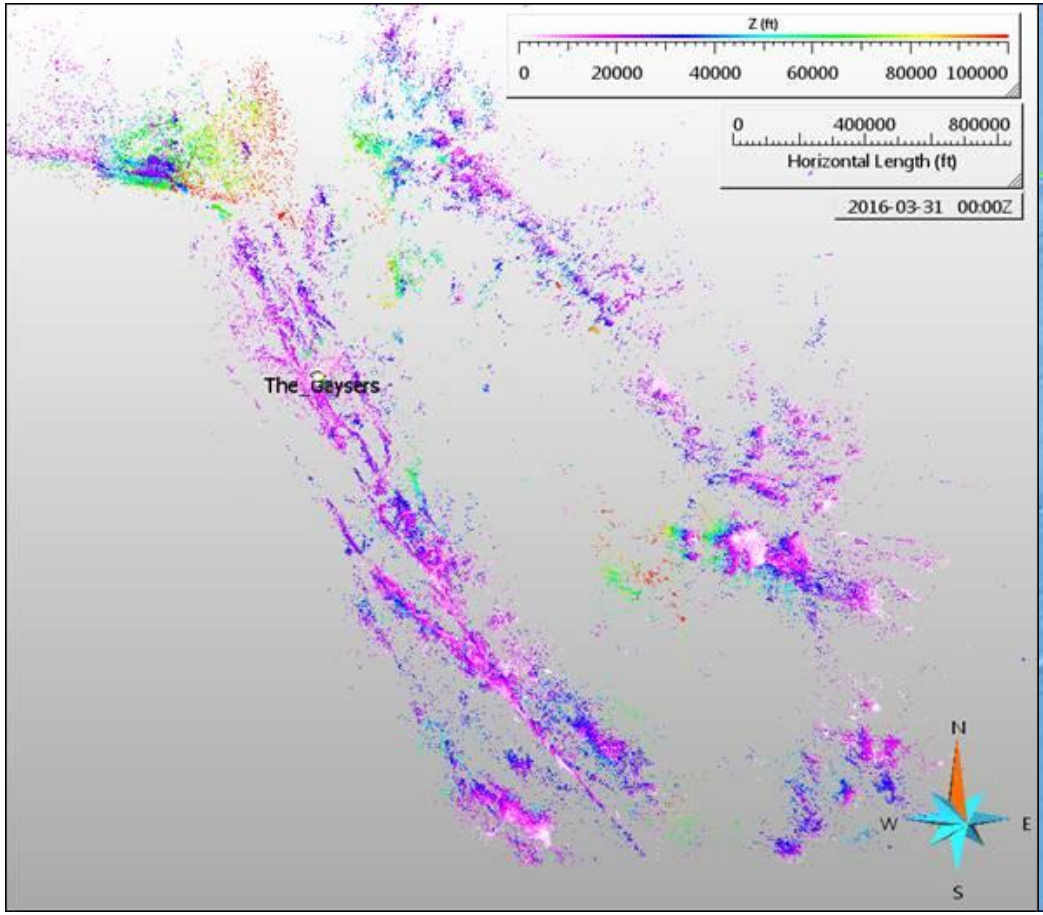
High heat content also limits the depth of faulting and fracturing at The Geysers.

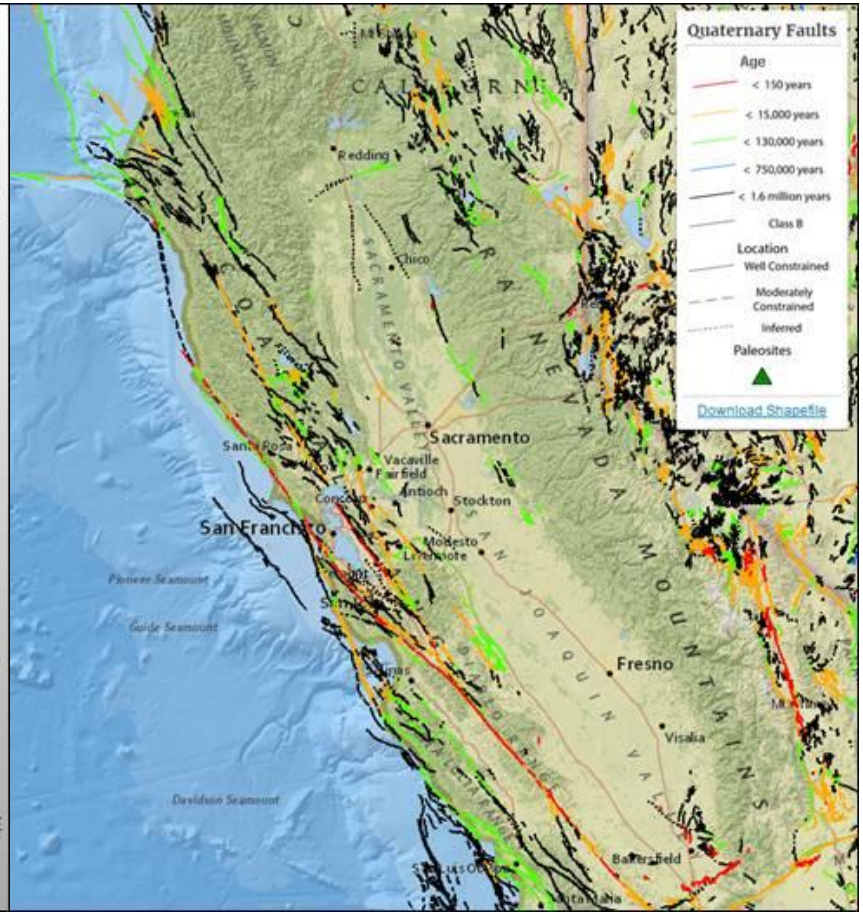
Rocks deeper than the brittle/ductile transition depth behave plastically

Seismic Monitoring Advisory Committee Meeting

Regional Seismicity Analysis

All Northern California Refined USGS Seismicity Hypocenters in 3D Project





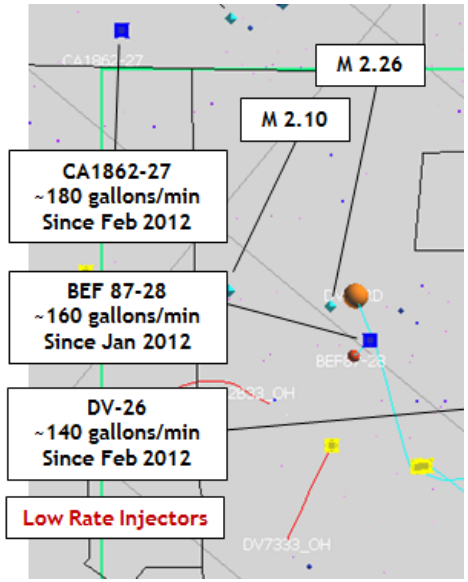
Calpine Geysers Water Injection Goals

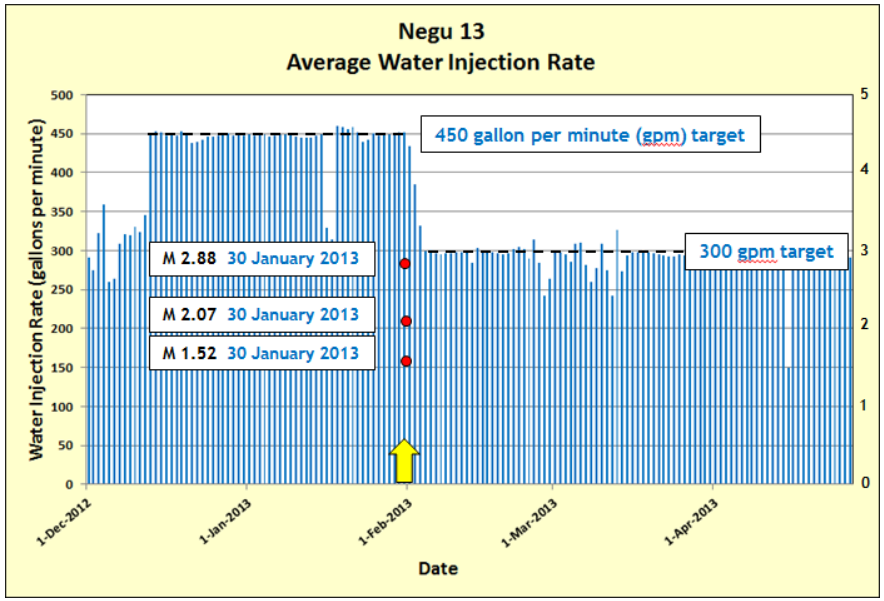
Improve Injection Distribution

- Expansion to northwest and away from communities
- Additional injection wells
- Shallow low-rate injectors (~150 gallons/minute)

Minimize Injection Rate Variations

- Individual wells and field-wide
- Emphasis on limited variation for wells nearest communities
- Suitable injection rates per well continually evaluated (dependent on local geology)
- Designed tests concerning injection rate variability far from communities (Prati 32 in NW Geysers)
- More gradual transition of SRGRP water for injection





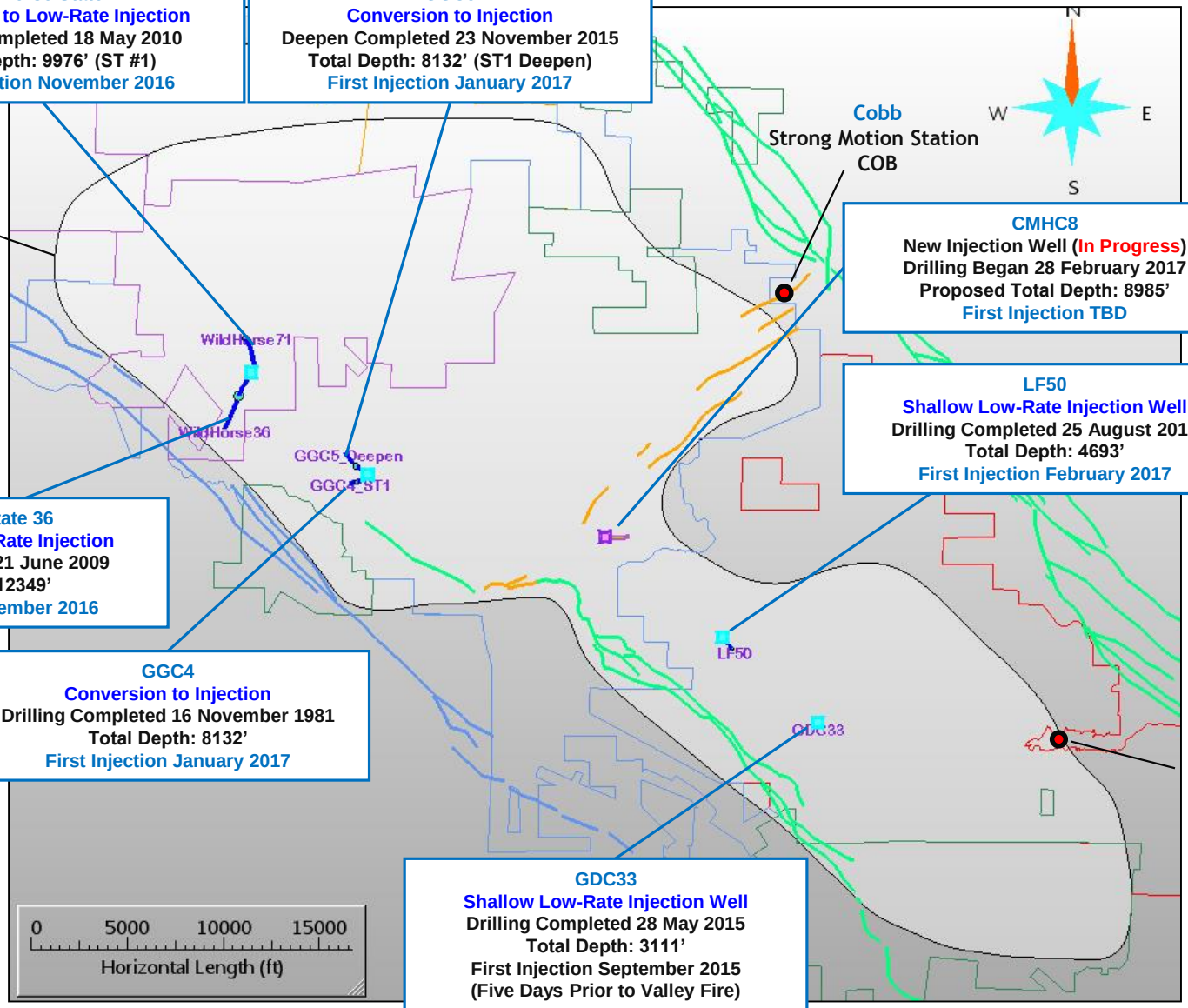
Seismic Monitoring Advisory Committee Meeting

Additional Water Injection Wells to Improve Injection Distribution

Wild Horse State 71
Conversion to Low-Rate Injection
Drilling Completed 18 May 2010
Total Depth: 9976' (ST #1)
First Injection November 2016

GGC5
Conversion to Injection
Deepen Completed 23 November 2015
Total Depth: 8132' (ST1 Deepen)
First Injection January 2017

The Geysers Productive Steam Reservoir Outline



Cobb
Strong Motion Station
COB

CMHC8
New Injection Well (In Progress)
Drilling Began 28 February 2017
Proposed Total Depth: 8985'
First Injection TBD

LF50
Shallow Low-Rate Injection Well
Drilling Completed 25 August 2015
Total Depth: 4693'
First Injection February 2017

Wild Horse State 36
Conversion to Low-Rate Injection
Drilling Completed 21 June 2009
Total Depth: 12349'
First Injection November 2016

GGC4
Conversion to Injection
Drilling Completed 16 November 1981
Total Depth: 8132'
First Injection January 2017

Anderson Springs
Strong Motion Station
ADS2

GDC33
Shallow Low-Rate Injection Well
Drilling Completed 28 May 2015
Total Depth: 3111'
First Injection September 2015
(Five Days Prior to Valley Fire)

Resumed Injection February 2017

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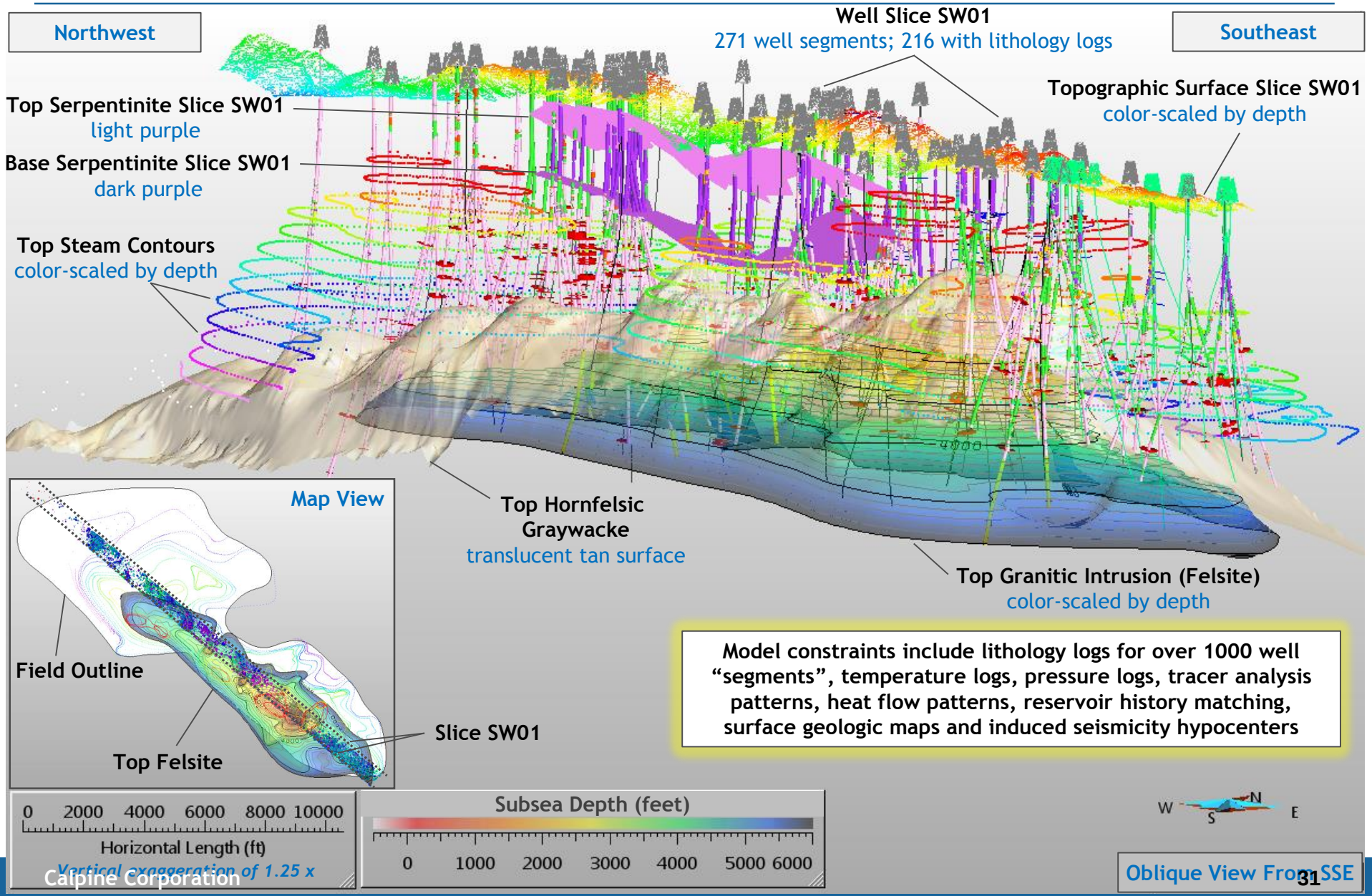
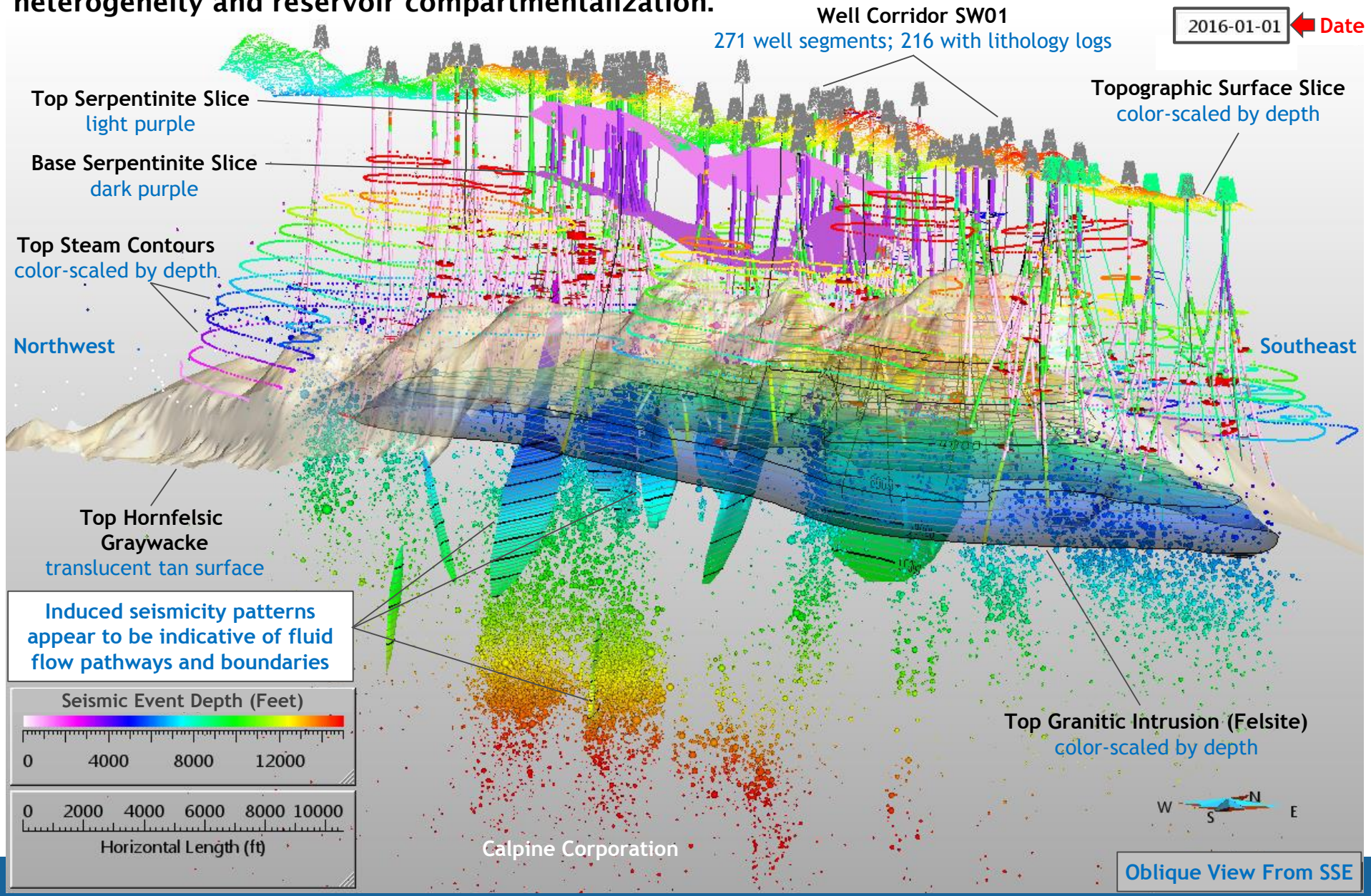
3D Structural Model Building with Paradigm Geophysical SKUA GOCAD Software



Model constraints include lithology logs for over 1000 well "segments", temperature logs, pressure logs, tracer analysis patterns, heat flow patterns, reservoir history matching, surface geologic maps and induced seismicity hypocenters

Seismic Monitoring Advisory Committee Meeting

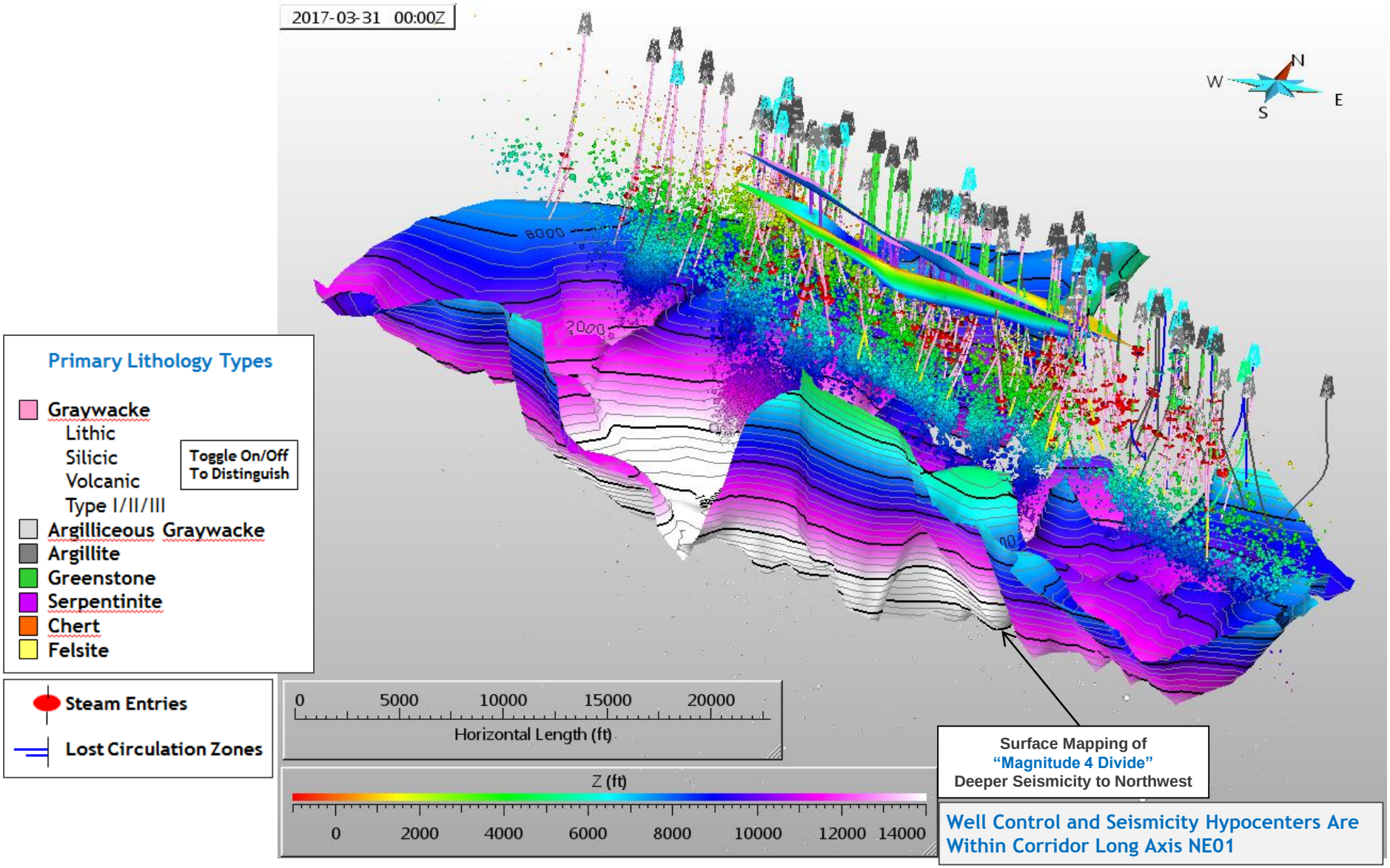
3D Structural Model Building Goal: Improved reservoir management and induced seismicity mitigation through a refined understanding of fluid flow paths, fluid boundaries, reservoir heterogeneity and reservoir compartmentalization.



Seismic Monitoring Advisory Committee Meeting

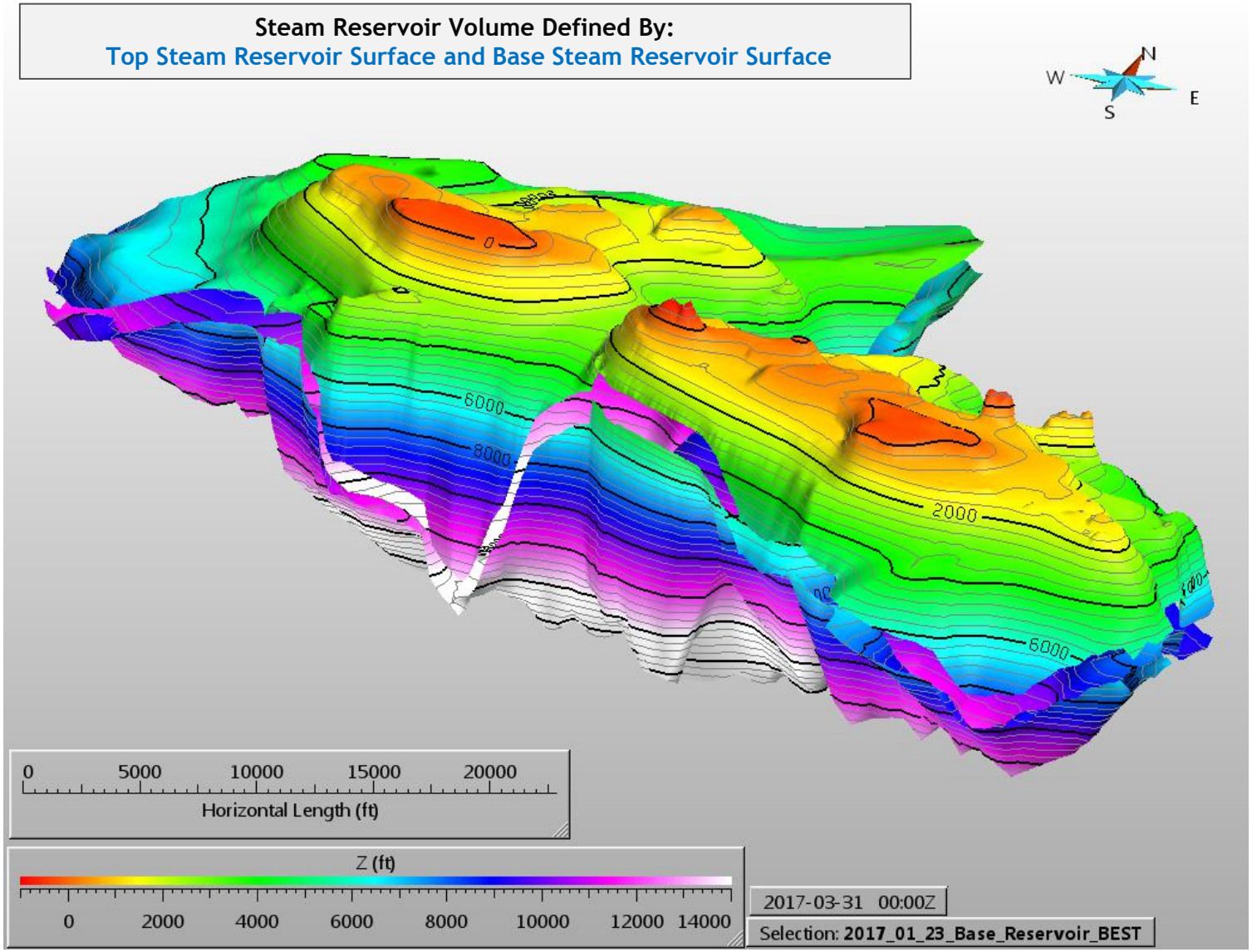
3D Structural and Stratigraphic Model Workflow

In Progress: Fieldwide Cell-Based Geological and Reservoir Model Development



Well Control and Seismicity Hypocenters Are Within Corridor Long Axis NE01

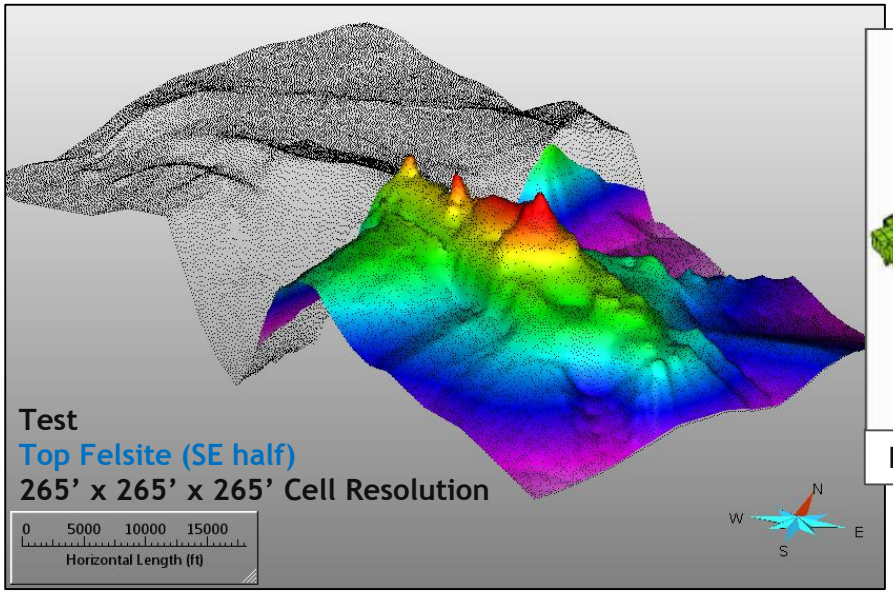
3D Structural and Stratigraphic Model Workflow
In Progress: Fieldwide Cell-Based Geological and Reservoir Model Development

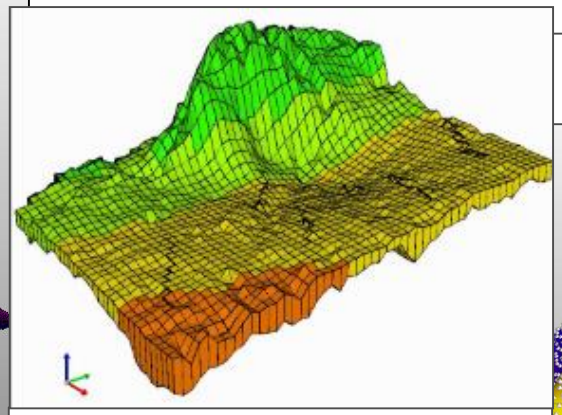


Seismic Monitoring Advisory Committee Meeting

3D Structural and Stratigraphic Model Workflow

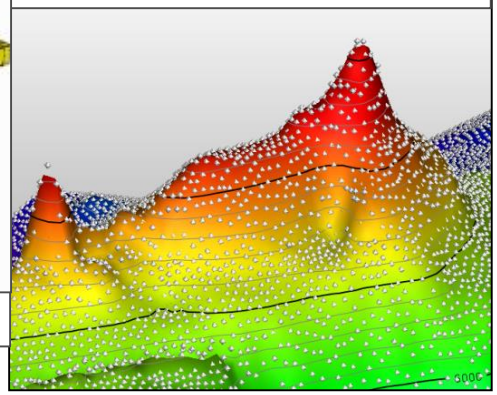
In Progress: Fieldwide Cell-Based Geological and Reservoir Model Development

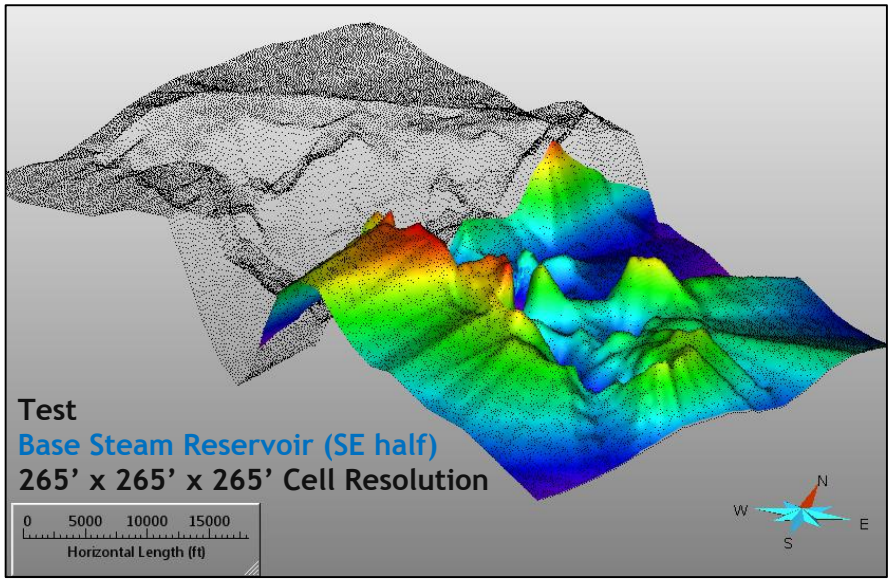


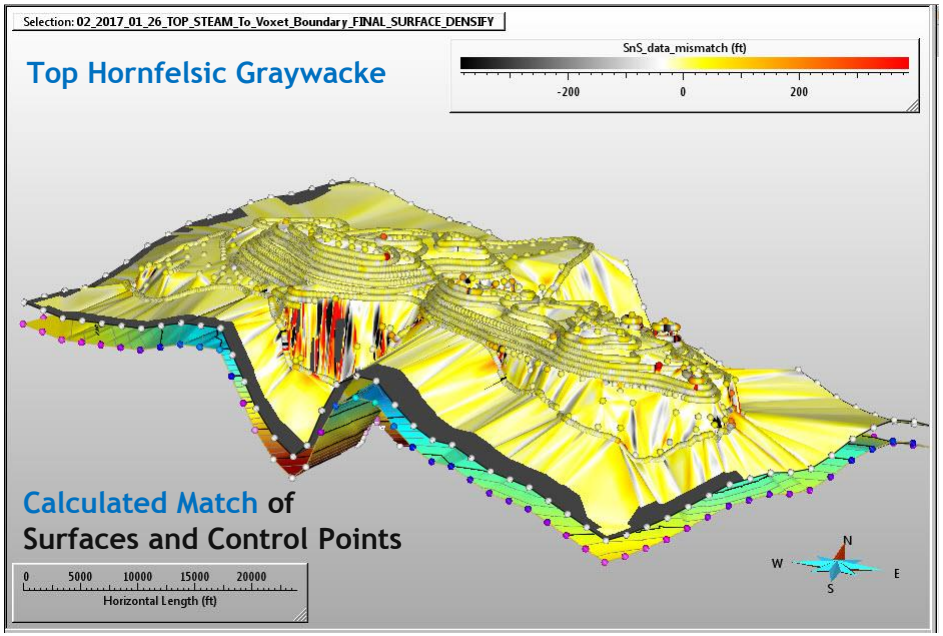


Limited Volume of Cell-Based Model

Visual Match of
Surface and Control Points





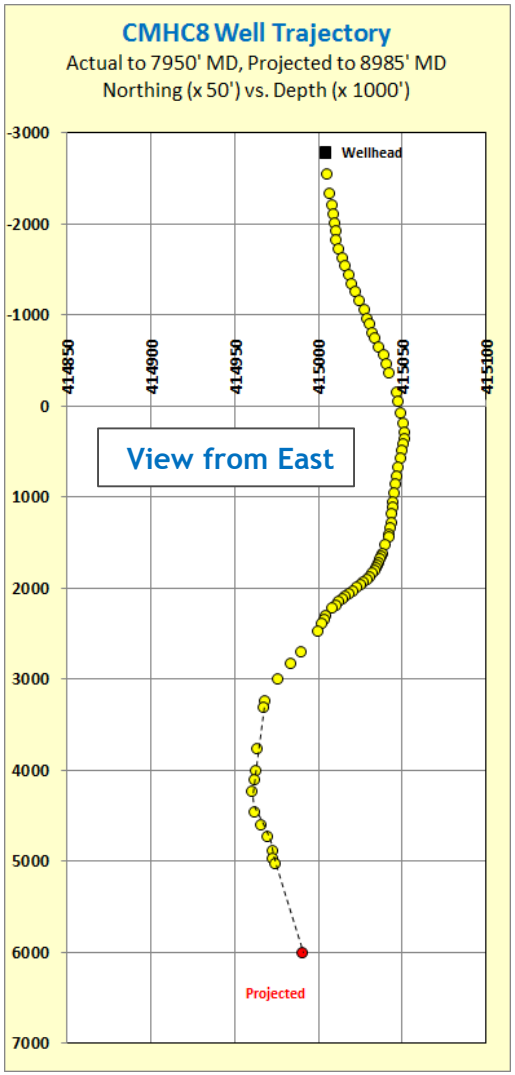


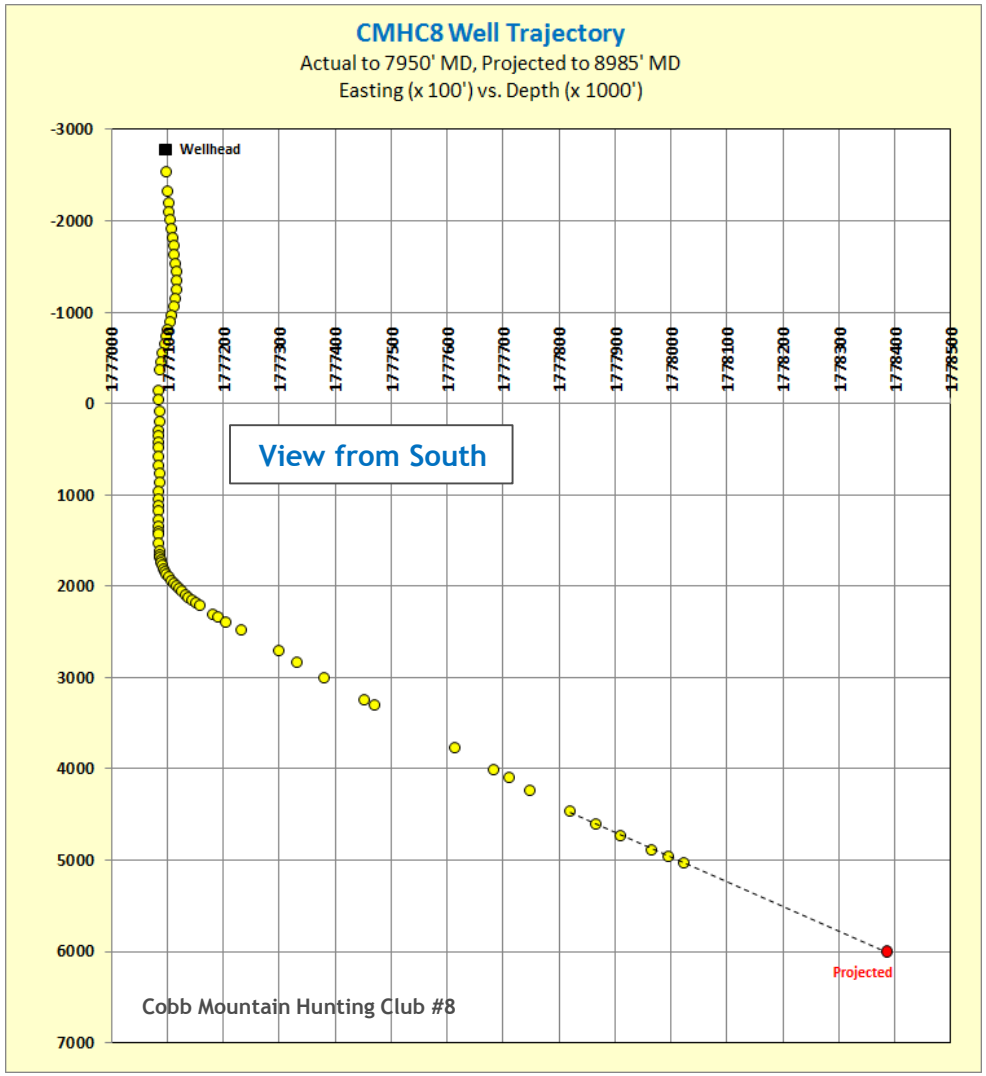
Seismic Monitoring Advisory Committee Meeting

3D Real-Time Drilling Analysis - CMHC 8 Water Injection Well Trajectory

Actual Well Trajectory	Yellow
Projected Well Trajectory	Red

Actual Trajectory to 7950' MD; Projected to 8985' MD





Seismic Monitoring Advisory Committee Meeting

3D Real-Time Drilling Analysis - CMHC 8 Water Injection Well Trajectory

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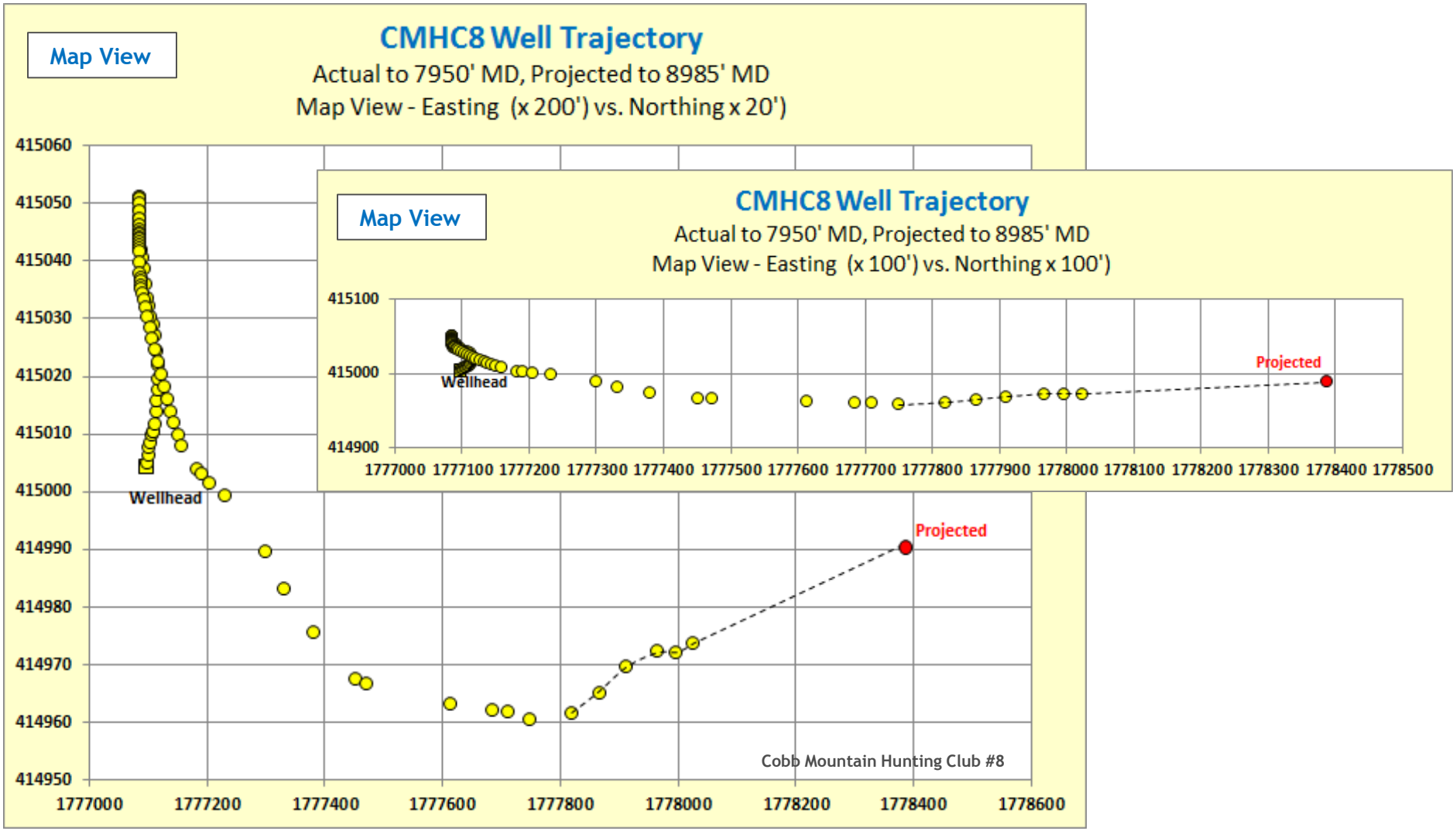
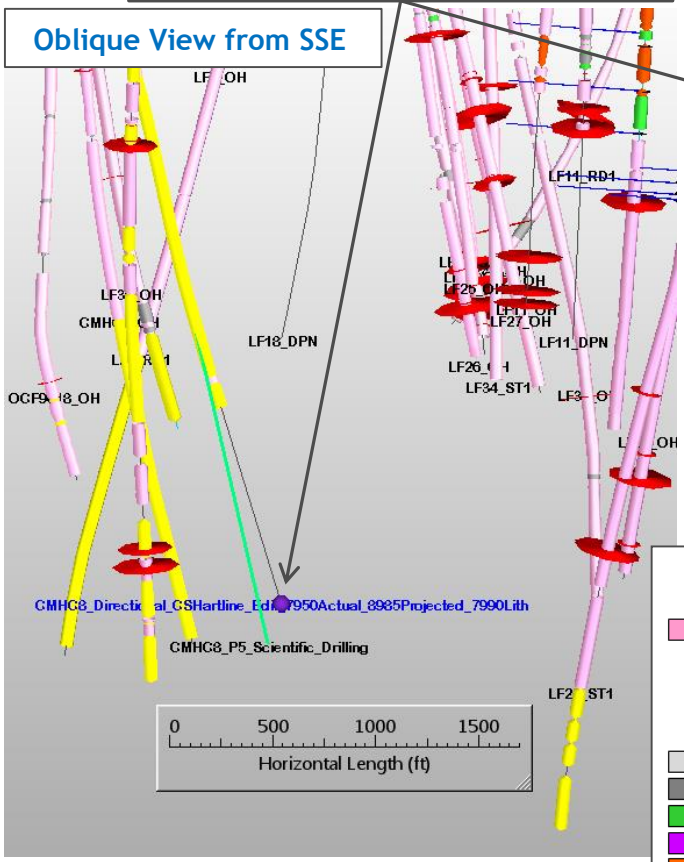


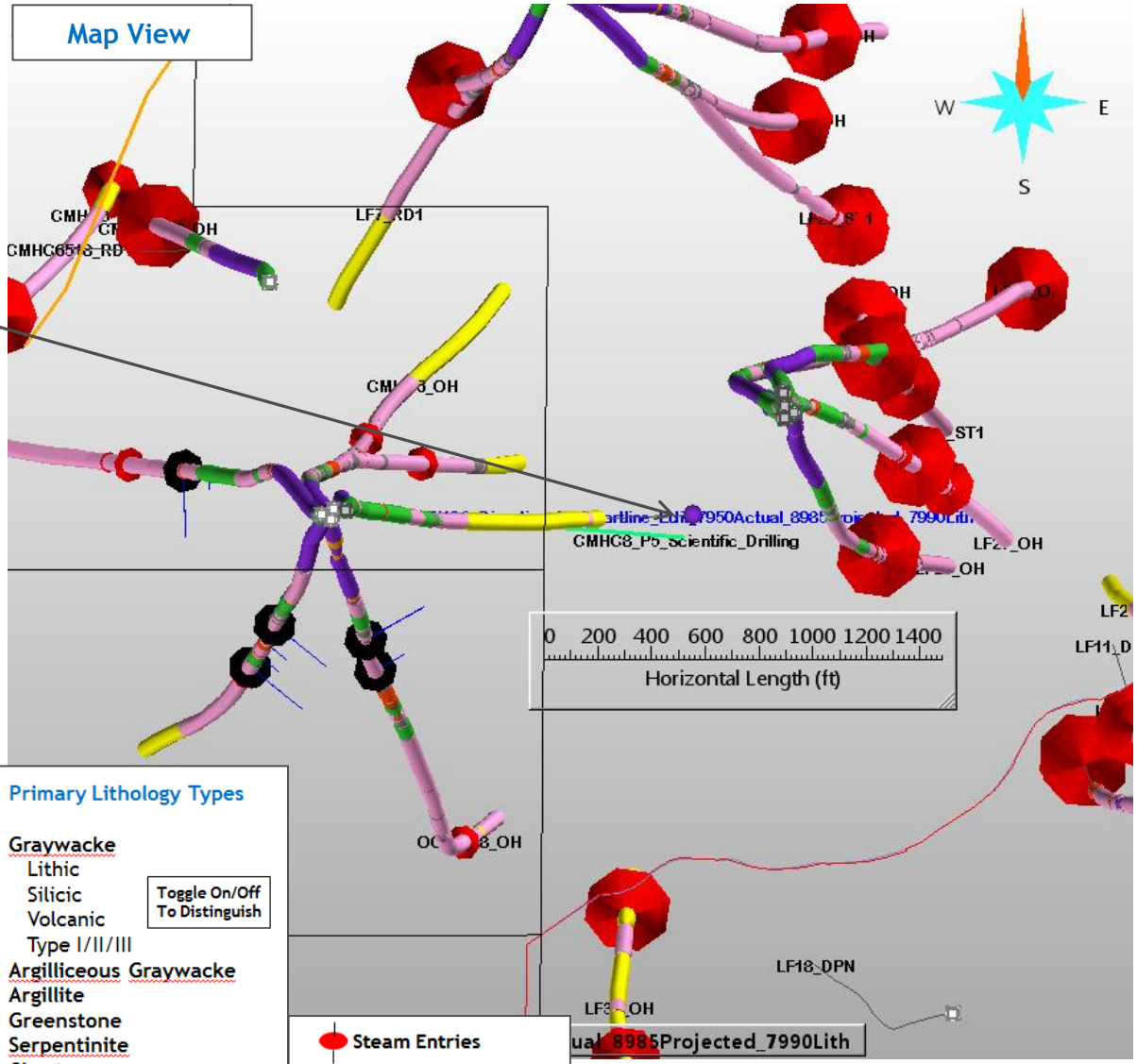
Seismic Monitoring Advisory Committee Meeting

3D Real-Time Drilling Analysis - CMHC 8 Water Injection Well Trajectory

CMHC8 is currently projected to reach a target depth of 6000' subsea at the following coordinates:

1778386' Easting
414990' Northing
8985' Measured Depth at TD
6000' Subsea Depth at TD





Primary Lithology Types

- Graywacke
  - Lithic
  - Silicic
  - Volcanic
  - Type I/II/III
- Argilliceous Graywacke
- Argillite
- Greenstone
- Serpentinite
- Chert
- Felsite

Toggle On/Off To Distinguish

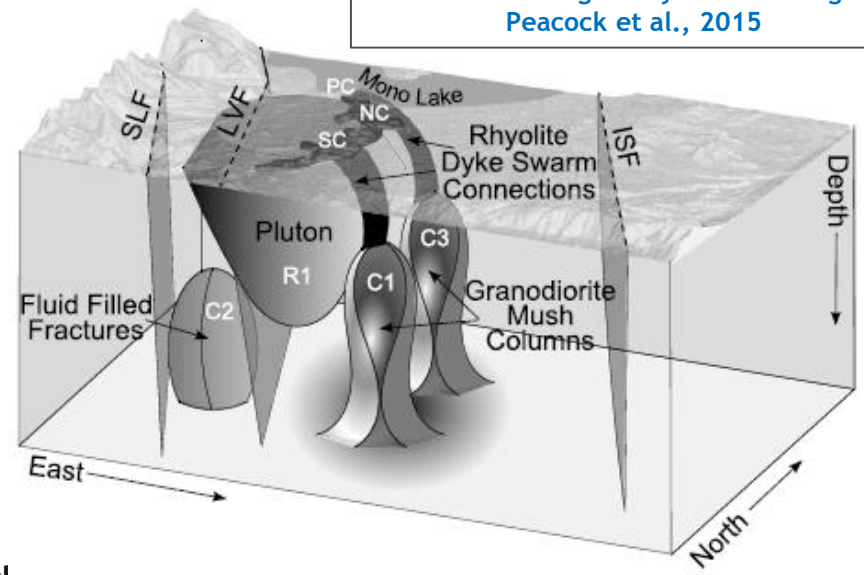
- Steam Entries
- Lost Circulation Zones

Seismic Monitoring Advisory Committee Meeting

Additional Subsurface Research

US Geological Survey Magnetotelluric (MT) Data Acquisition at The Geysers

Conceptual Geological Model of the Mono Basin in the Long Valley Volcanic Region. Peacock et al., 2015



US Geological Survey

Margaret Mangan, Ph. D. - Scientist-in-Charge
Jared Peacock - Mendenhall Post Doctoral Student

Calpine Corporation The Geysers

Mark Walters - Senior Geologist
Craig Hartline - Senior Geophysicist

Background

- Solar energy and lightning cause natural variations in the earth's magnetic field and produce electrical currents.
- Different rocks, sediments and geological structures respond differently to these electrical currents.
- Magnetotelluric surveys *passively* measure the variations in electrical current response.
- Magnetotellurics is a very important tool in deep earth research.

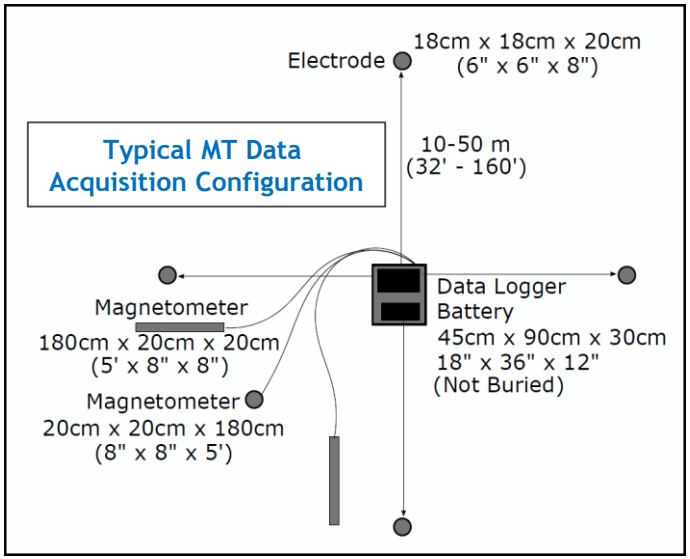
Program

- Summer 2017 magnetotelluric data acquisition
- ~50 survey locations in the north Geysers

Goal

- Create a three-dimensional subsurface electrical resistivity model.
- Better understand the development of The Geysers geothermal resource through an extended series of magmatic intrusions.
- Create a conceptual geological model of very complex deep subsurface at The Geysers.

- *This is anticipated to contribute to reservoir management and induced seismicity mitigation efforts at The Geysers.*



Seismic Monitoring Advisory Committee Meeting

Additional Seismic Monitoring and Research

California Energy Commission Electric Program Investment Charge (EPIC) Program EPC-16-021

Accepted Proposal

High-Resolution Micro-Earthquake Imaging of Flow Paths Using a Dense Seismic Network and Fast-Turnaround, Automated Processing

Program Goal

Development of advanced, low-cost, microseismic imaging for high-resolution spatial and temporal images of subsurface fluid flow, flow barriers and heterogeneity in producing geothermal fields. The project will focus on microseismicity imaging challenges that are unique to geothermal reservoirs.

Improved 3D and time-lapse subsurface resolution is anticipated to assist with seismicity mitigation efforts at The Geysers.

Applicant

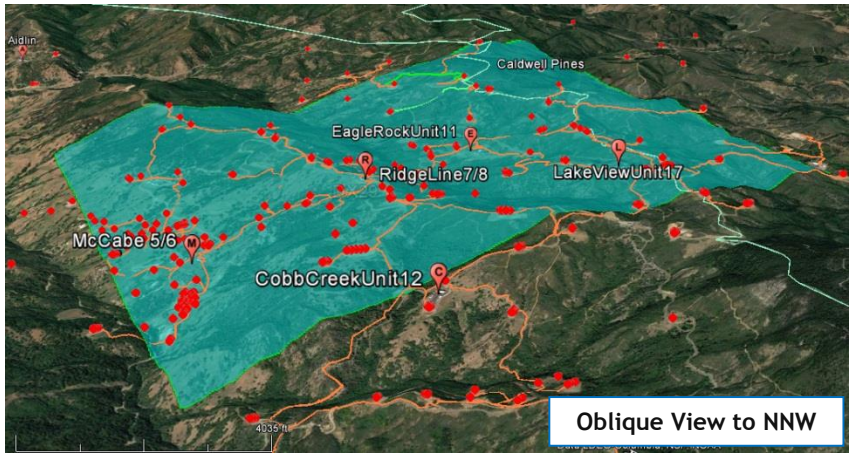
Lawrence Berkeley National Laboratory

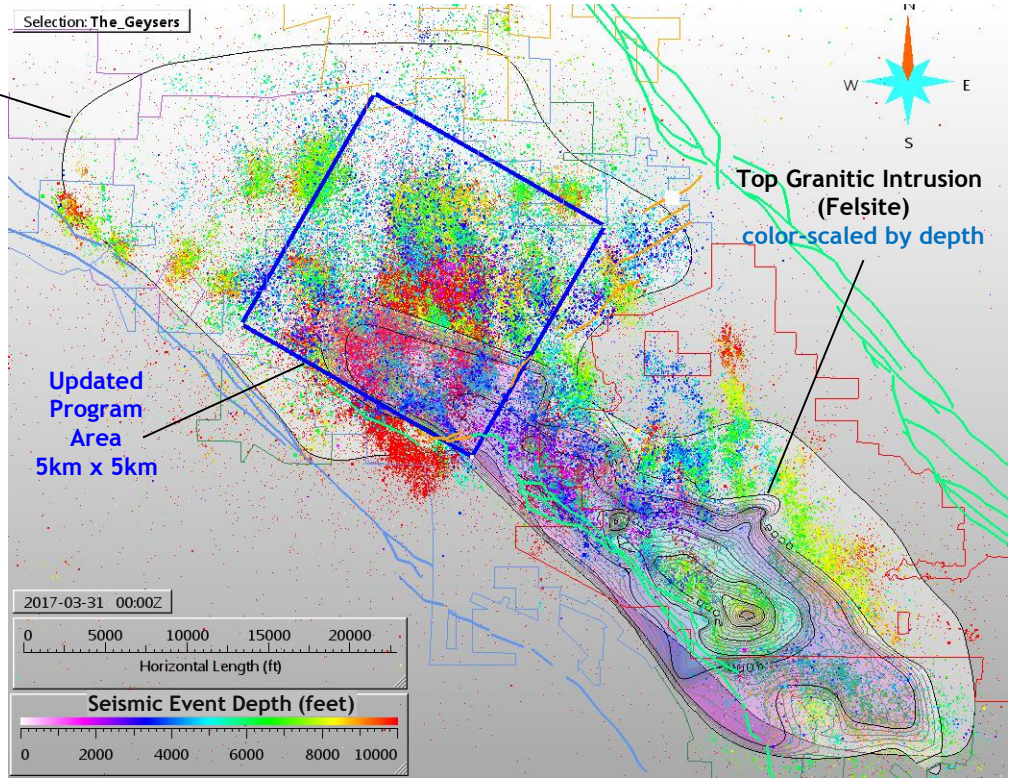
Project Partners

Calpine Corporation
Array Information Technology

California Energy Commission Funds Recommended

$1,672,639





Seismic Monitoring Advisory Committee Meeting

Additional Seismic Monitoring and Research

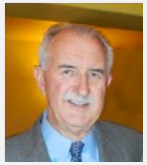
California Energy Commission Electric Program Investment Charge (EPIC) Program
Approval of Grant Funding Opportunity 16-301

Project Team

Kurt Nihei
Principal Investigator
Geomechanics
LBNL

Roland Gritto
(Co-PI)
Geophysics
Array Info Tech

Larry Hutchings
Geophysics
Jarpe Data Solution



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Katie Freeman
Geophysics
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Bill Foxall
Geophysics
LBNL

Seiji Nakagawa
Rock Physics
LBNL

Yves Guglielmi
Geomechanics
LBNL

Pierre Jeane
Geomechanics
LBNL

Steve Jarpe
Geophysics
Jarpe Data Solution

Michelle Robertson, Geophysicist, LBNL
Ramsey Haught, Geophysicist, Consultant

Proposed Technical Advisory Committee

Ernie Majer
Induced Seismicity
LBNL/SNL

Craig Hartline
Induced Seismicity
Calpine Corporation

Brian Bonner
Rock Physics
LBNL (LLNL)

Lane Johnson
Earthquake Seismology
LBNL (UC Berkeley)

Schedule

2017				2018				2019				2020
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Task 1 - Project Management												
	Task 2 - Dense Network Design											
		Task 3 - Fast-Turnaround, High-Resolution Imaging										
				Task 4 - Field Demo								
					Task 5 - Rock Physics Transforms							

Seismic Research Collaboration with Seismic Warning Systems

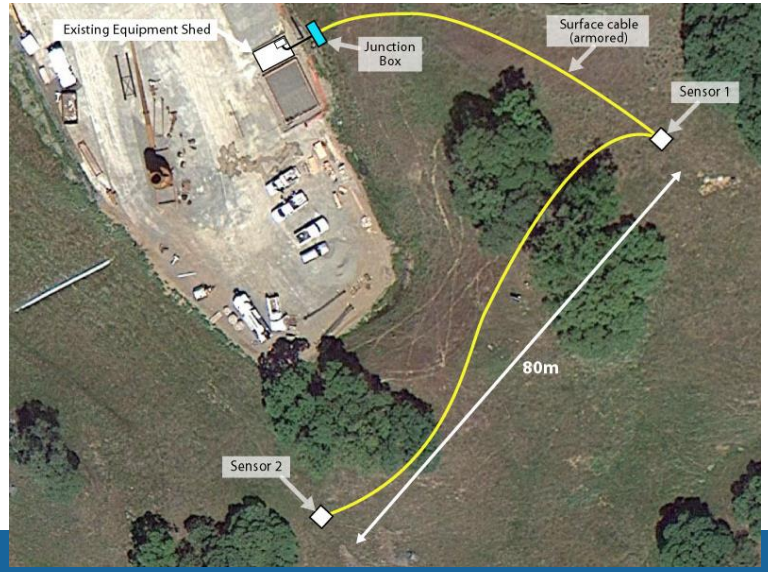
Early Detection and Warning System for Natural Earthquakes

SEISMIC WARNING SYSTEMS

Primary Goal

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

Two test sensors at The Geysers Prati 32 well pad.
Installation date 15 September 2014.
Tied in to Calpine power and communications.



Geysers Project Goals

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

Seismic Monitoring Advisory Committee Meeting

Seismic Research Collaboration with Zizmos

Test Installation at Calpine Geothermal Visitor Center
Additional Installations Soon at Geysers Administration Center and West Administration Center

Early Detection and Warning System for Natural Earthquakes

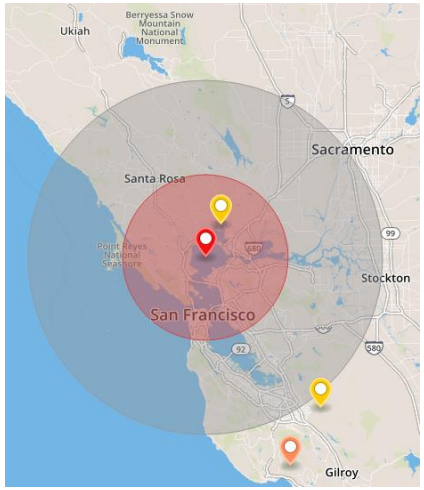
Primary Goal

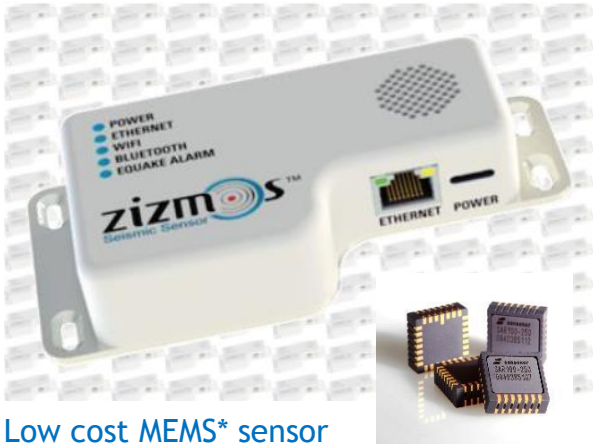
Cost-effective cloud-connected seismic network that provides earthquake early-warning and high-resolution shake maps. Designed to complement existing scientific solutions with the addition of low-cost mobile and wireless sensors.

Hybrid approach to reduce casualties and provide structural engineers, utilities, transportation officials, and property owners with unprecedented near real-time information about the shake hazards. Backed by the National Science Foundation ($250,000) and Verizon ($1,000,000).

Geysers Project Goals

Initial sensor placement at the Calpine Geothermal Visitor Center for testing of network and firewall issues. Expansion into The Geysers geothermal field for refinement of automated event detection and warning.





Low cost MEMS* sensor
Available Networking and Cloud Computing

Research Collaborations

Lawrence Berkeley National Laboratory

36 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

Initiating collaboration for high-resolution imaging of fluid flow paths using a dense seismic network and automated processing

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

Seismic Warning Systems

Northwest Geysers test site for calibration of earthquake early warning systems

Zizmos

Geothermal Visitor Center test site for cloud-connected seismic network earthquake early warning systems