

**Seismic Monitoring  
Advisory Committee Review**

14 May 2012  
Geothermal Visitors Center  
Middletown, California

Reporting Period:  
1 October 2011 to 31 March 2012



**Reporting Period 01 October 2011 to 31 March 2012**

SMAC Area Water Injection and Seismicity  
Strong Motion Sensor Stations  
Strong Motion Data Analysis  
Field-Wide Water Injection and Seismicity

**Reporting Period 01 September 2011 to 29 Feb 2012**

SRGRP #17 Summary

**Historical Seismicity**

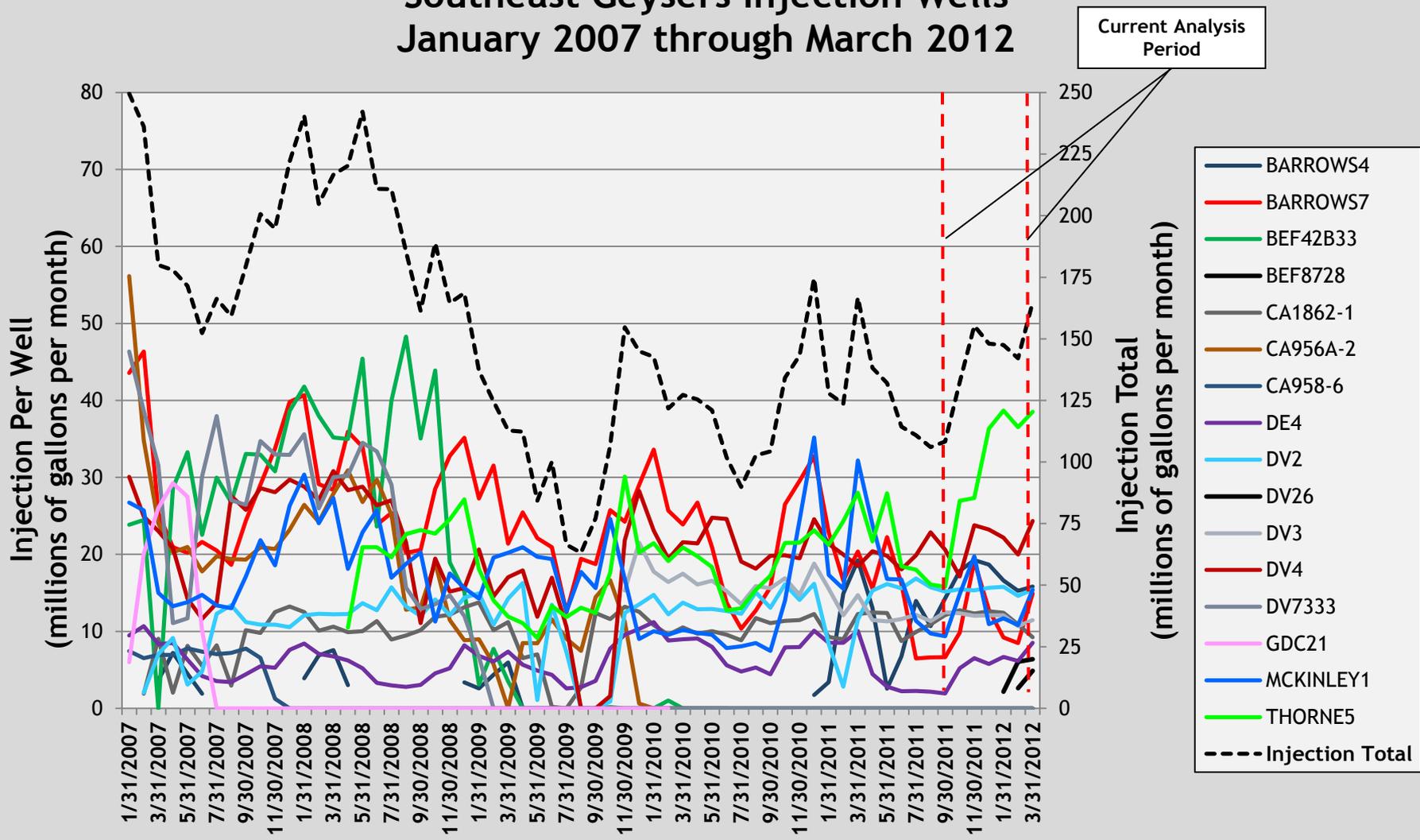
Field-wide Steam Production, Water Injection and Seismicity  
Seismic Energy Release Investigation

**Recent Seismicity Research Collaborations**

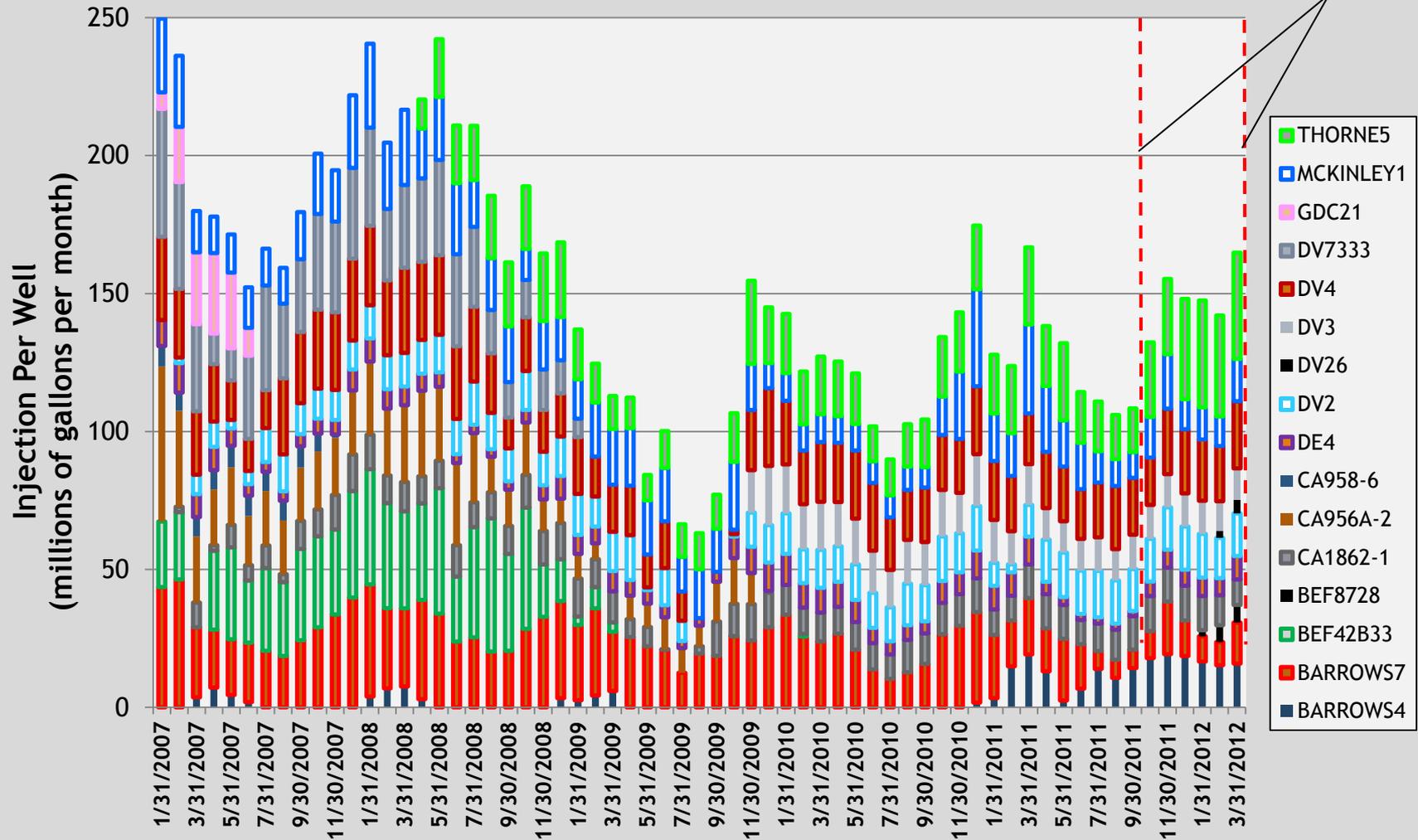
Lawrence Berkeley National Laboratory  
GEISER Consortium  
United States Geologic Survey

**Calpine's Communication and Public Relations**

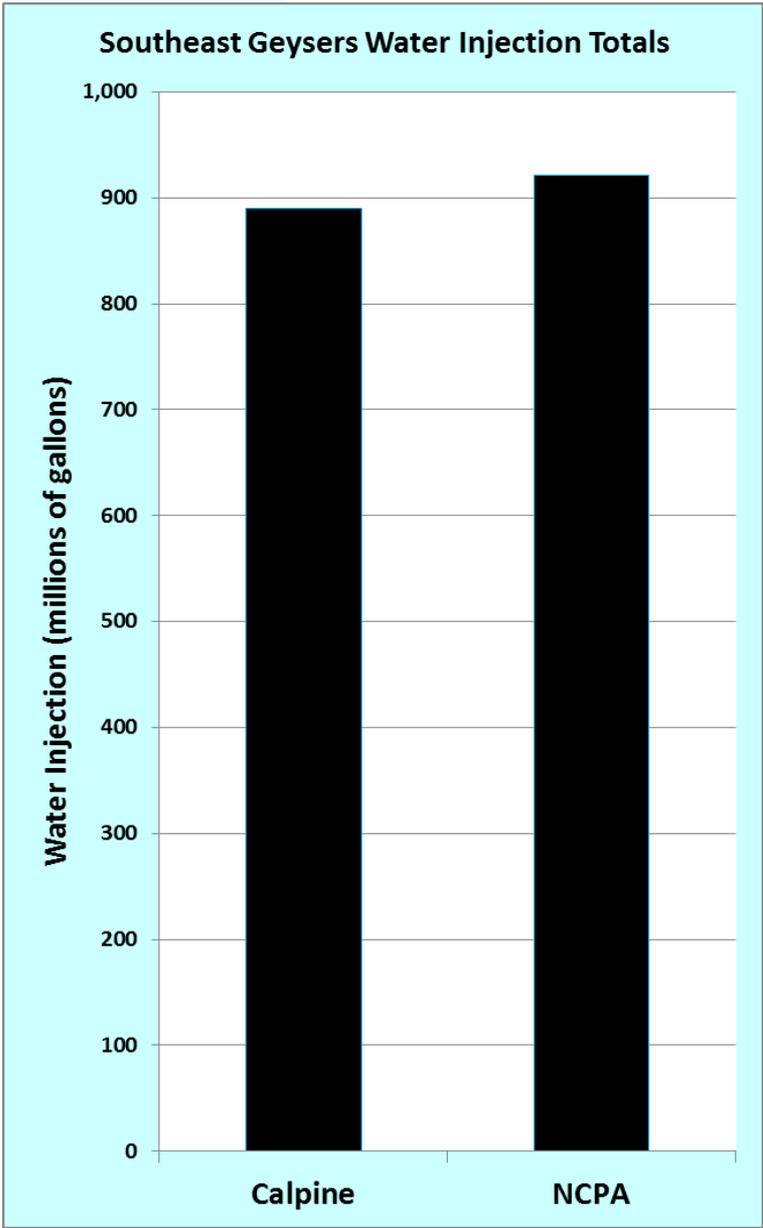
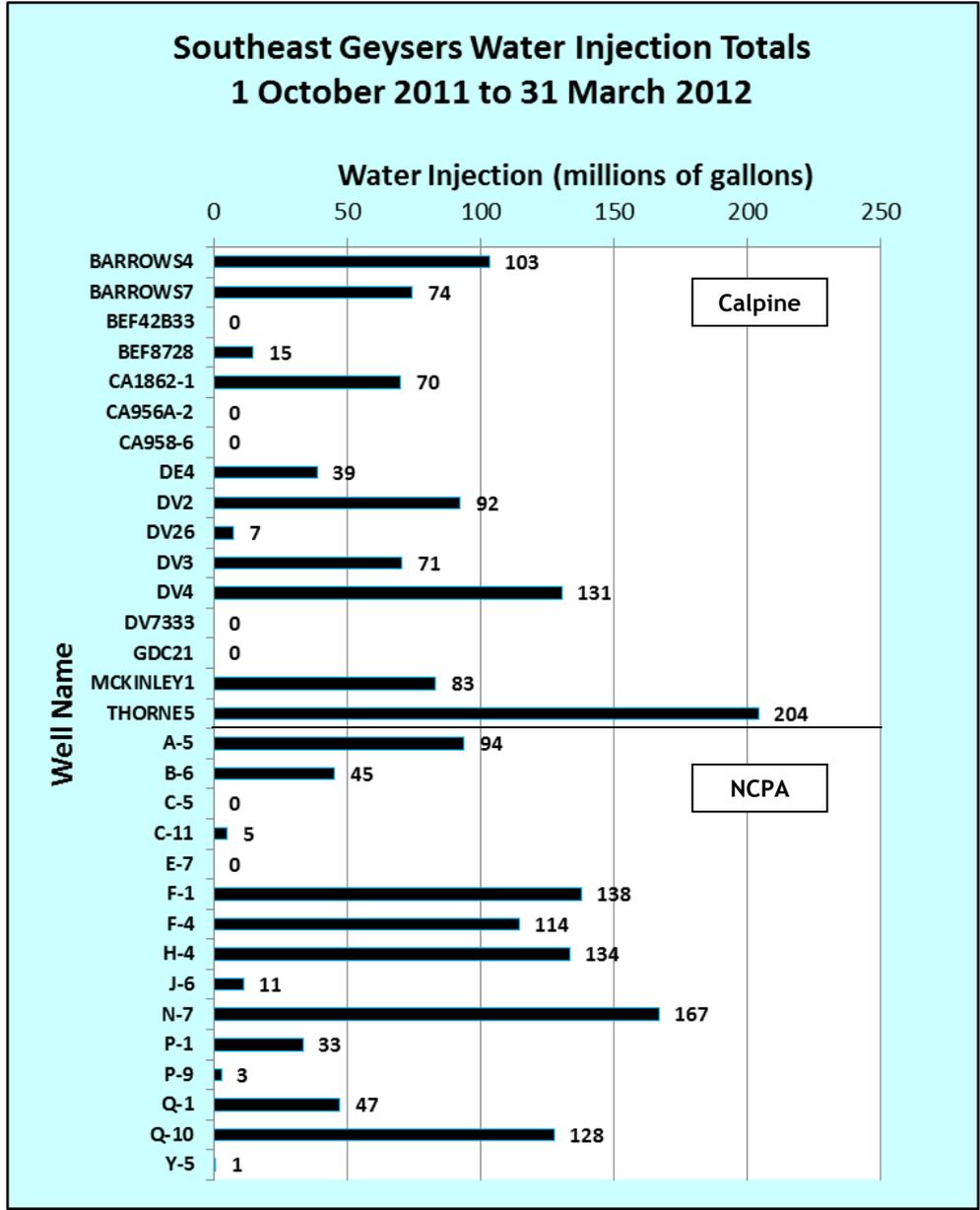
### Southeast Geysers Injection Wells January 2007 through March 2012



### Southeast Geysers Injection Wells January 2007 through March 2012



Current Analysis Period



# Seismic Monitoring Advisory Committee

## Southeast Geysers Seismicity and Injection

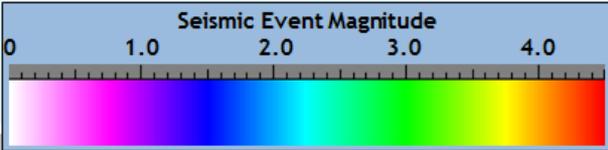


**Low Rate Injectors**

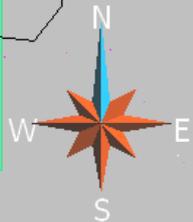
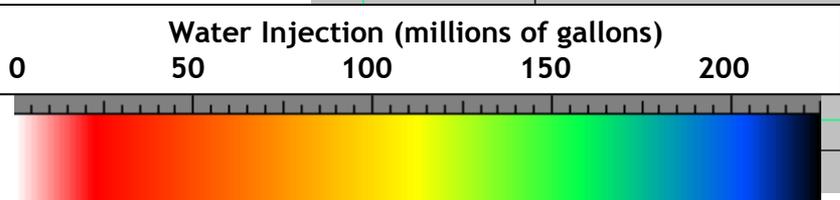
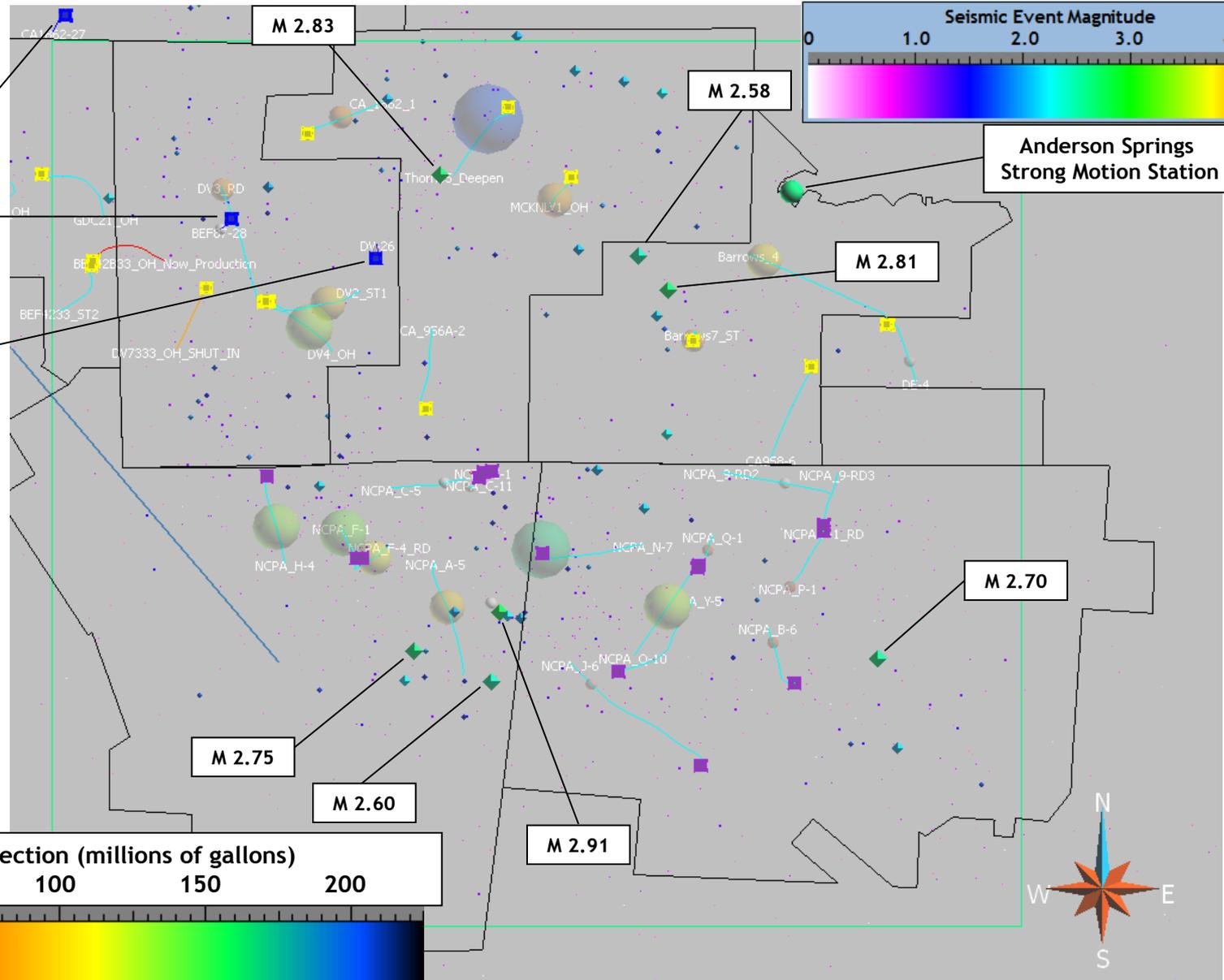
**CA1862-27**  
~180 gallons/min  
Since Feb 2012

**BEF 87-28**  
~160 gallons/min  
Since Jan 2012

**DV-26**  
~140 gallons/min  
Since Feb 2012



**Anderson Springs  
Strong Motion Station**



**Northern California Seismic Network  
 Seismicity Data**

**Southeast Geysers Seismicity Results as of 31 March 2012**

*Comparison of pre-SEGEP and post-SEGEP (equivalent annual rates in parentheses)*

<u>Time Period</u>	<u>Pre-SEGEP</u>	<u>SEGEP</u>	<u>Current Period</u>
Dates	Nov 1995 - Oct 1997	Nov 1997 - Sep 2011	Oct 2011- May 2012
Time Span (yrs)	2	14.42	0.5
<u>Seismic Events:</u>			
M $\geq$ 1.2	330 (165)	4508 (312)	141 (282)
M $\geq$ 2.0	46 (23)	644 (45)	25 (50)
M $\geq$ 3.0	10 (5)	35 (2.4)	0 (0)
M Maximum	3.7	4.3	2.9

**Anderson Springs Strong Motion**

Data loss from 26 Dec 2011 to 29 Dec 2011

AC power loss; system on battery until technician available; connection restored

**Cobb Strong Motion**

Data loss from 02 Sept 2011 to 12 Sept 2011

Not answering calls; memory card problem

Initial assessment by Calpine technician delayed several days

Jim Cullen replaced memory card

Data loss from 09 Nov 2011 to 30 Nov 2011

Cobb station not communicating (phone) beginning 08 Nov 2011.

Calpine technician not available for several days.

Jim Cullen available for on-site assessment and repair 29 Nov 2011

Internal phone modem replaced and electrical/power connections re-done on 30 Nov 2011

Data loss from 01 Dec 2011 to 12 Dec 2011

Determined that no files are being sent on 01 Dec 2011

Jim Cullen detected a memory card failure; repaired 11 Dec 2011 (waiting on part)

**Strong Motion System Reliability Limitations:**

Rural Power

Rural Communications

Lightning Strikes

Downed Lines



Anderson Springs ETNA  
Strong Motion Station

Memory cards have been a persistent problem and spares are now available.

#### Considering options for a long-term strong-motion monitoring solution

Spare ETNA parts: minimize delays in acquiring parts

Spare ETNA station: allowing repairs and upgrades to unit that is not currently in service

Additional strong-motion stations:

Rural power or solar panel w/ battery back-up (?)

Rural communication or stand-alone units requiring download at intervals (?)

ETNA instrument or different device manufacturer (?)

Modern seismic monitoring devices generally expect an Ethernet connection

Downloaded data from stand-alone units requires processing before analysis

#### Site Selection for Additional Strong Motion Stations

URS Corporation contracted for:

Analysis of EQ Hotline and existing reports

On-site assessment of structures and local conditions

Ivan Wong: Principal Seismologist; Seismic Hazards Group; URS Corporation

Melinda Wright: Senior Geologist; Calpine Corporation

Craig Hartline: Senior Geophysicist; Calpine Corporation

#### Toll-free seismic hotline (1-877-4GEYSER) continues operation

94 voicemails transcribed and reviewed 01 Oct 2011 to 31 Mar 2011

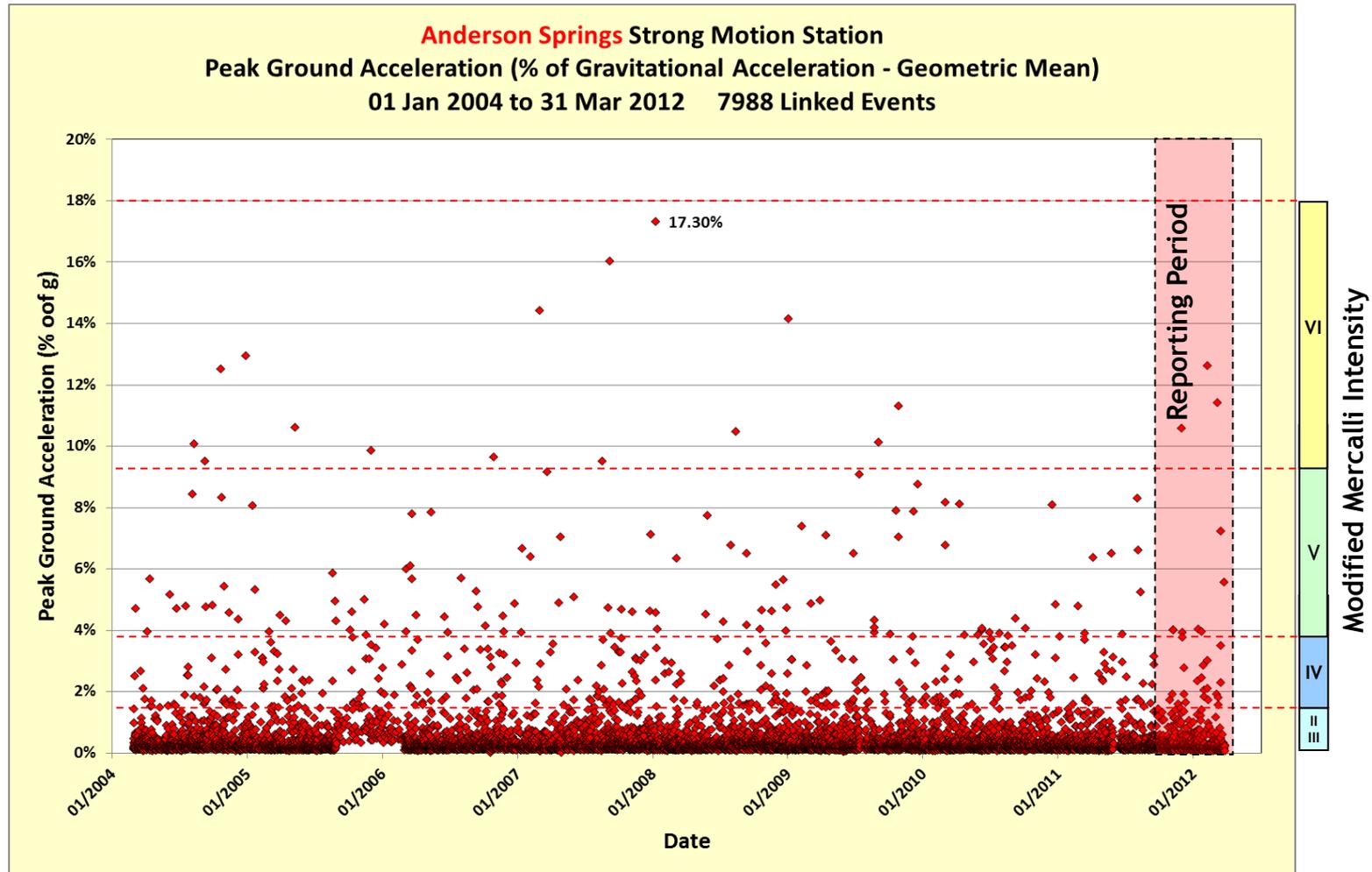
#### 17 calls for Sunday, 12 Feb 2012 M 4.26 seismic event

20% of all calls were from a very limited number of callers concerning noise / vibration

# Seismic Monitoring Advisory Committee Meeting

## 1 October 2011 to 31 March 2012

### Anderson Springs Peak Ground Acceleration

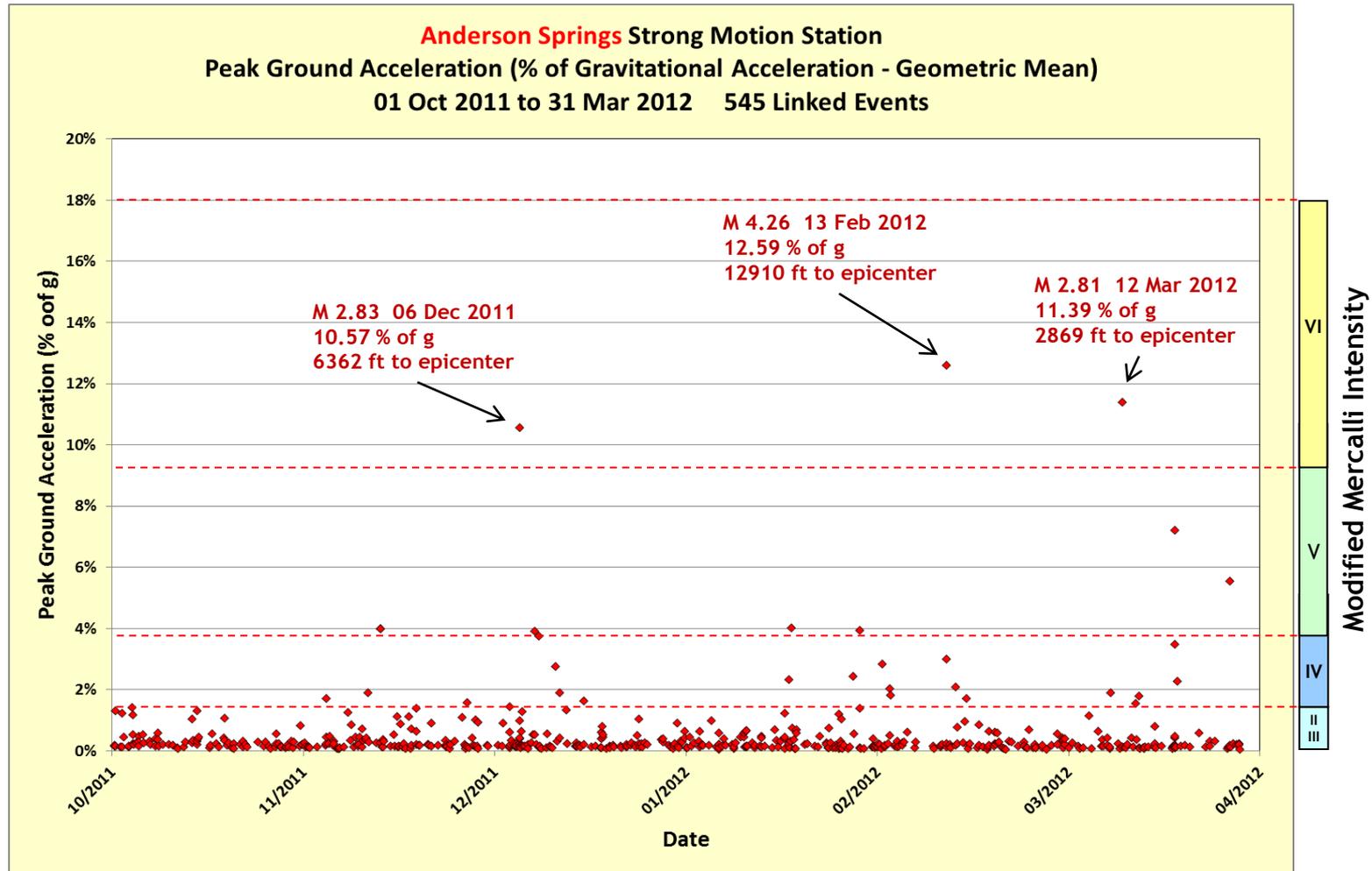


Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	None	None	None	Very Light	Light	Moderate	Mod/Heavy	Heavy	Very Heavy
Peak Acceleration (% of g)	< 0.17	0.17 - 1.4	1.4 - 3.9	3.9 - 9.2	9.2 - 18.0	18.0 - 34.0	34.0 - 65.0	65.0 - 124.0	> 124.0
Peak Velocity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

## 1 October 2011 to 31 March 2012

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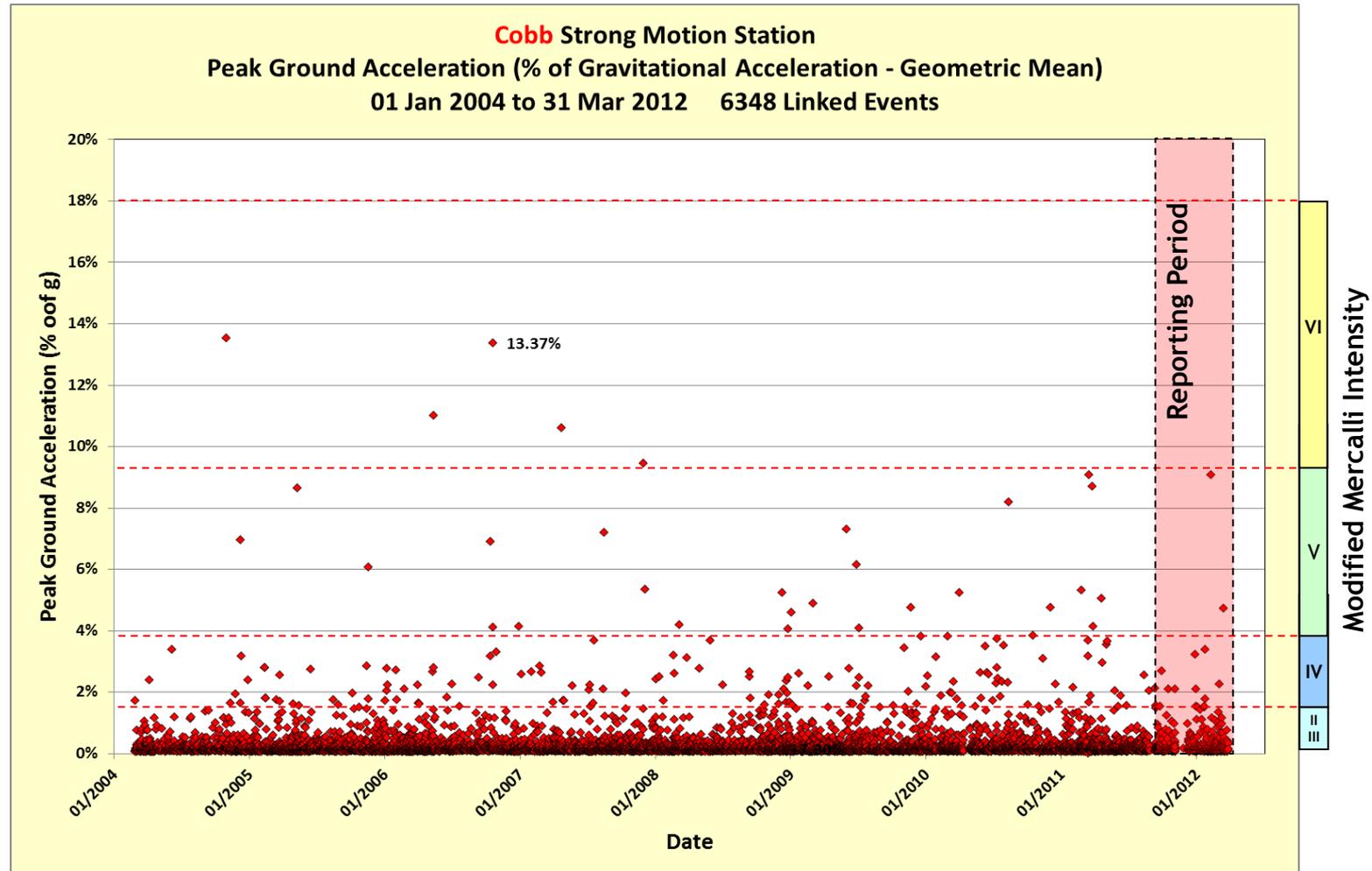


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# Seismic Monitoring Advisory Committee Meeting

## 1 October 2011 to 31 March 2012

### Cobb Peak Ground Acceleration

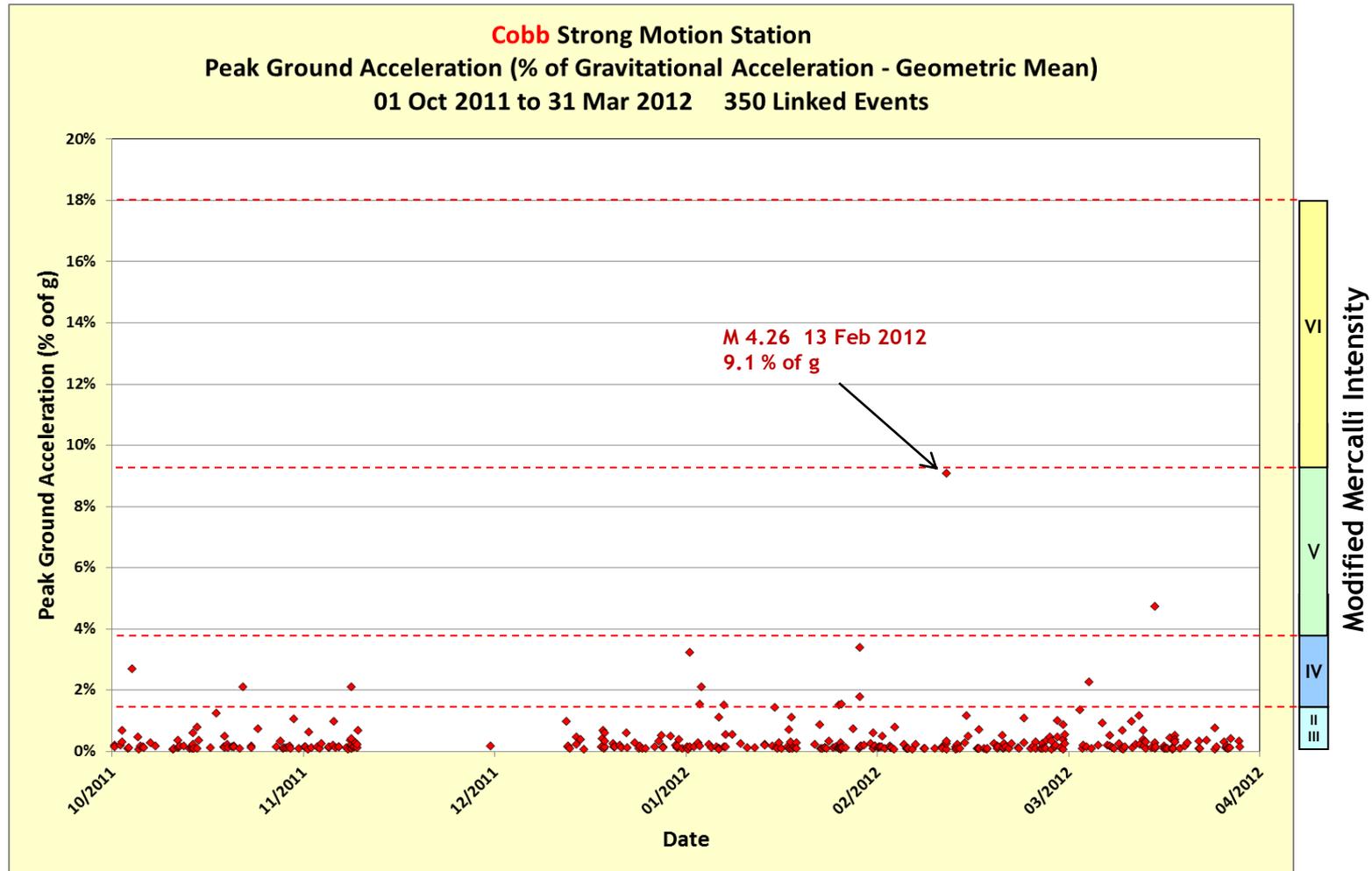


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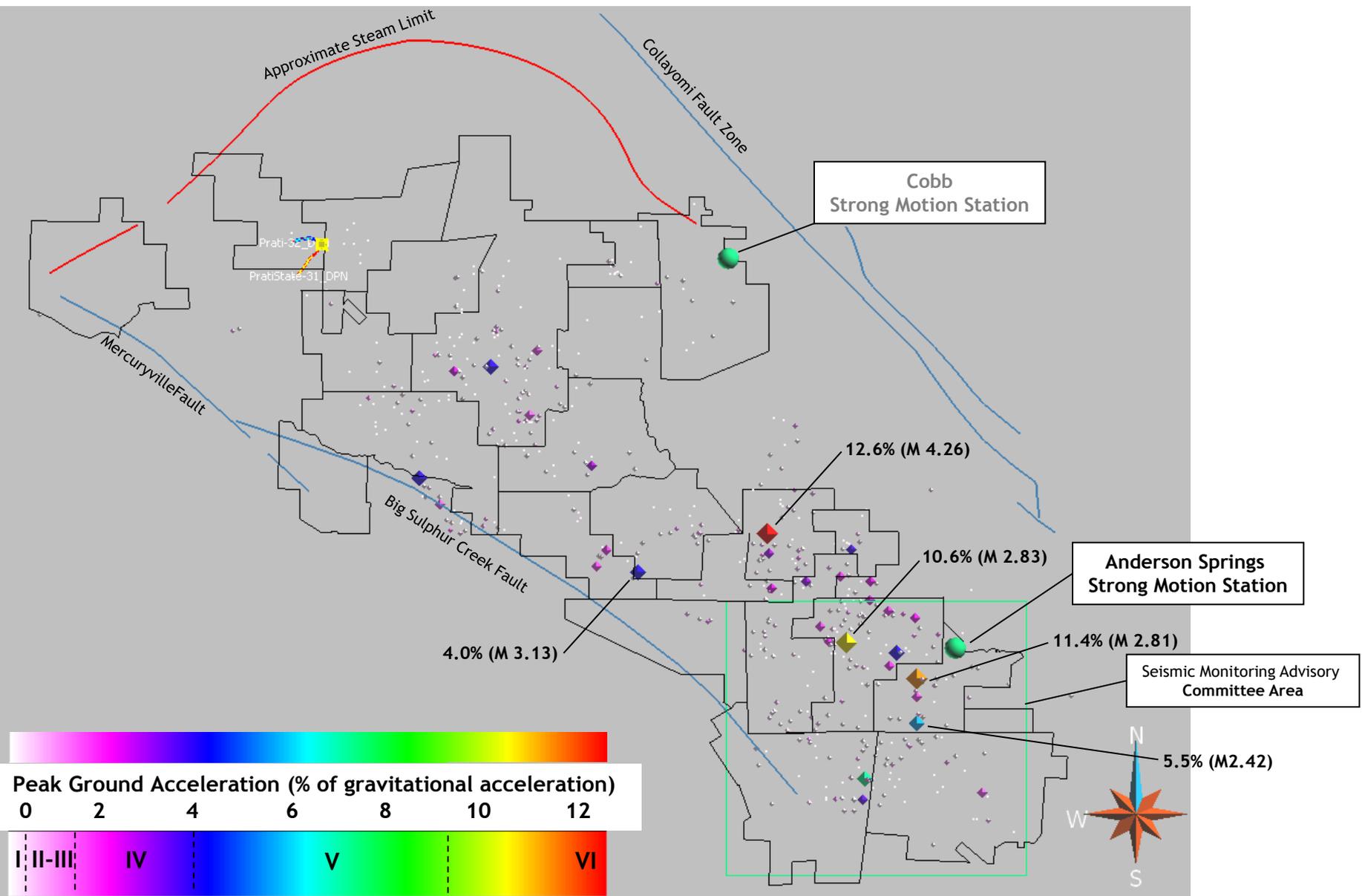


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## 1 October 2011 to 31 March 2012

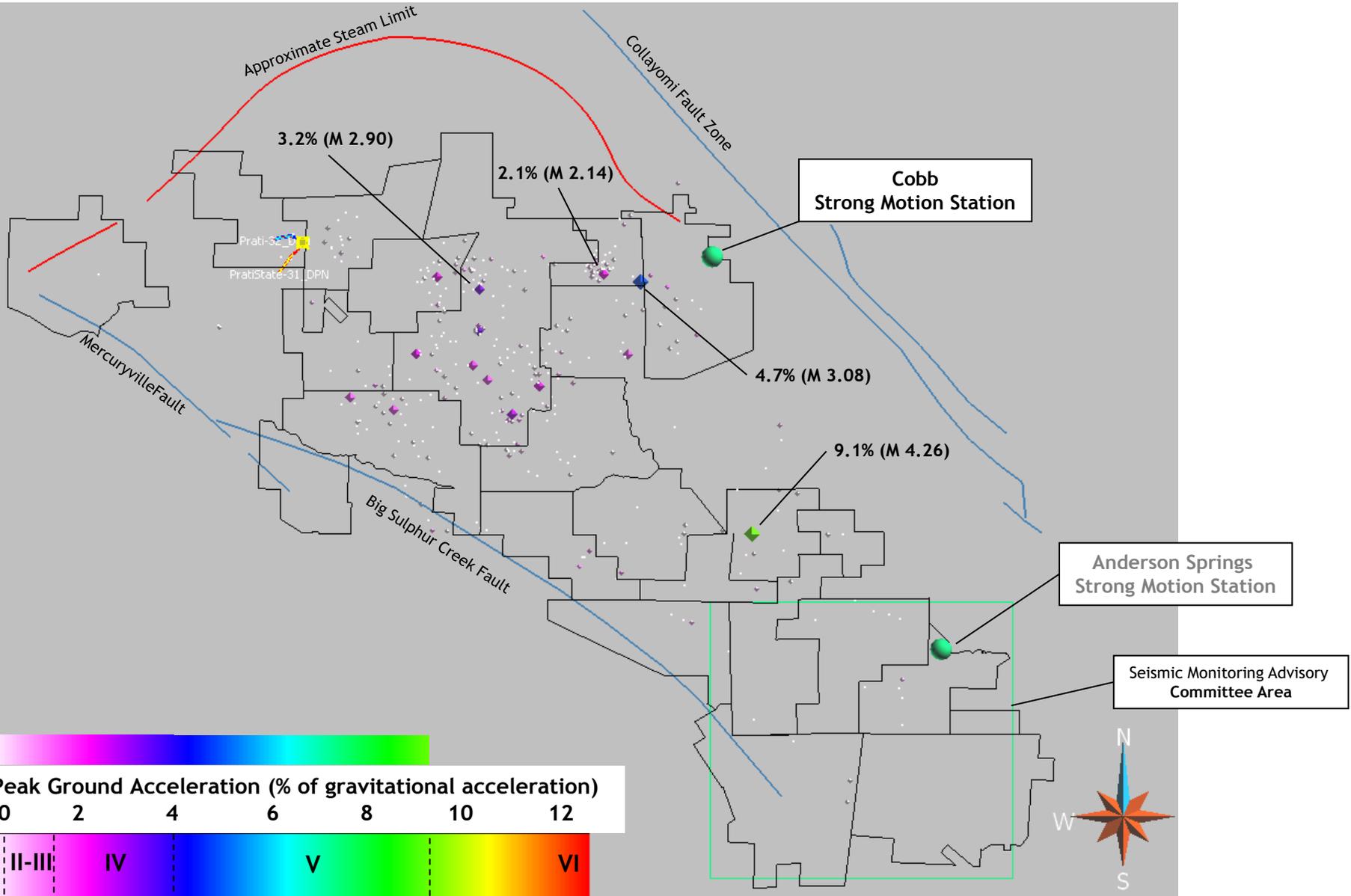
### Anderson Springs Peak Ground Acceleration



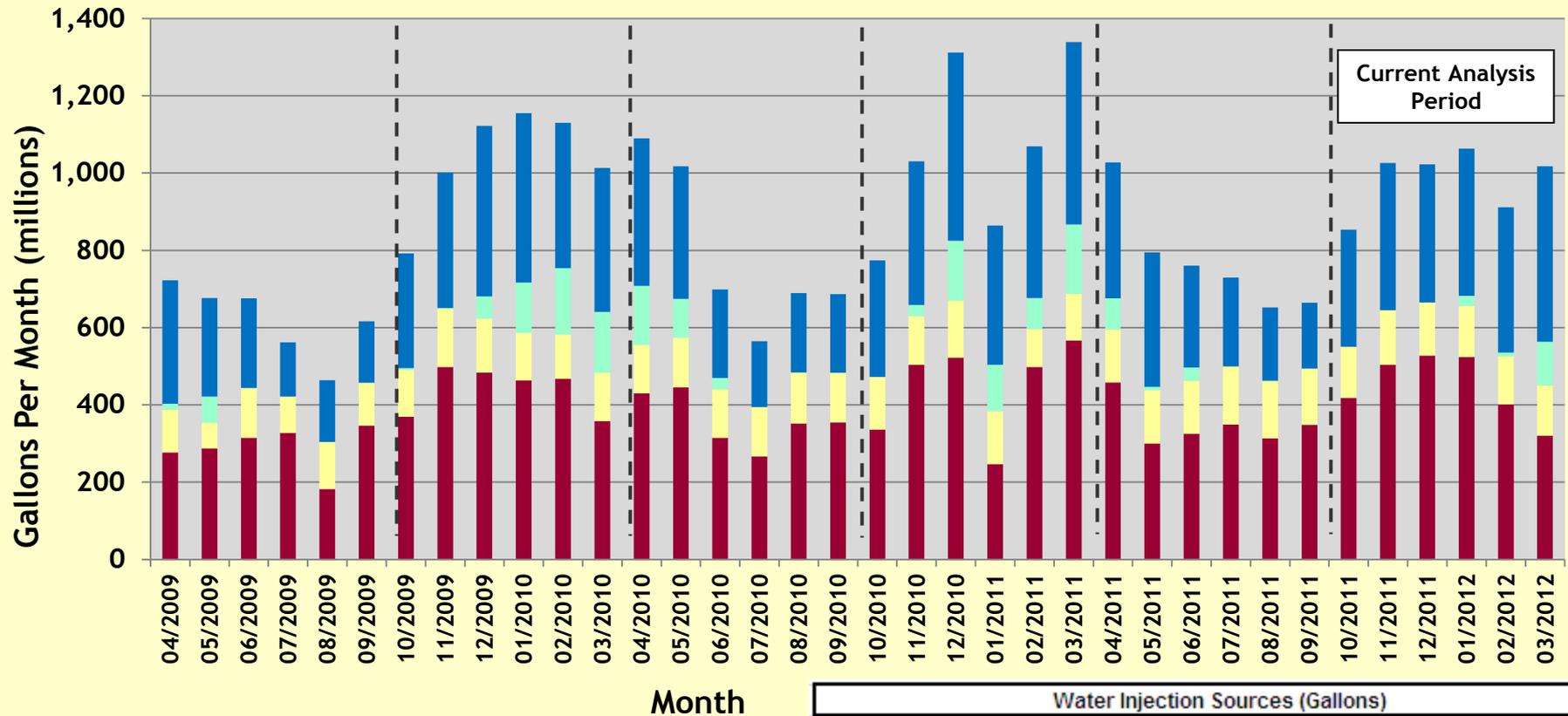
# Seismic Monitoring Advisory Committee Meeting

## 1 October 2011 to 31 March 2012

### Cobb Peak Ground Acceleration



### Water Injection Sources April 2008 to March 2012



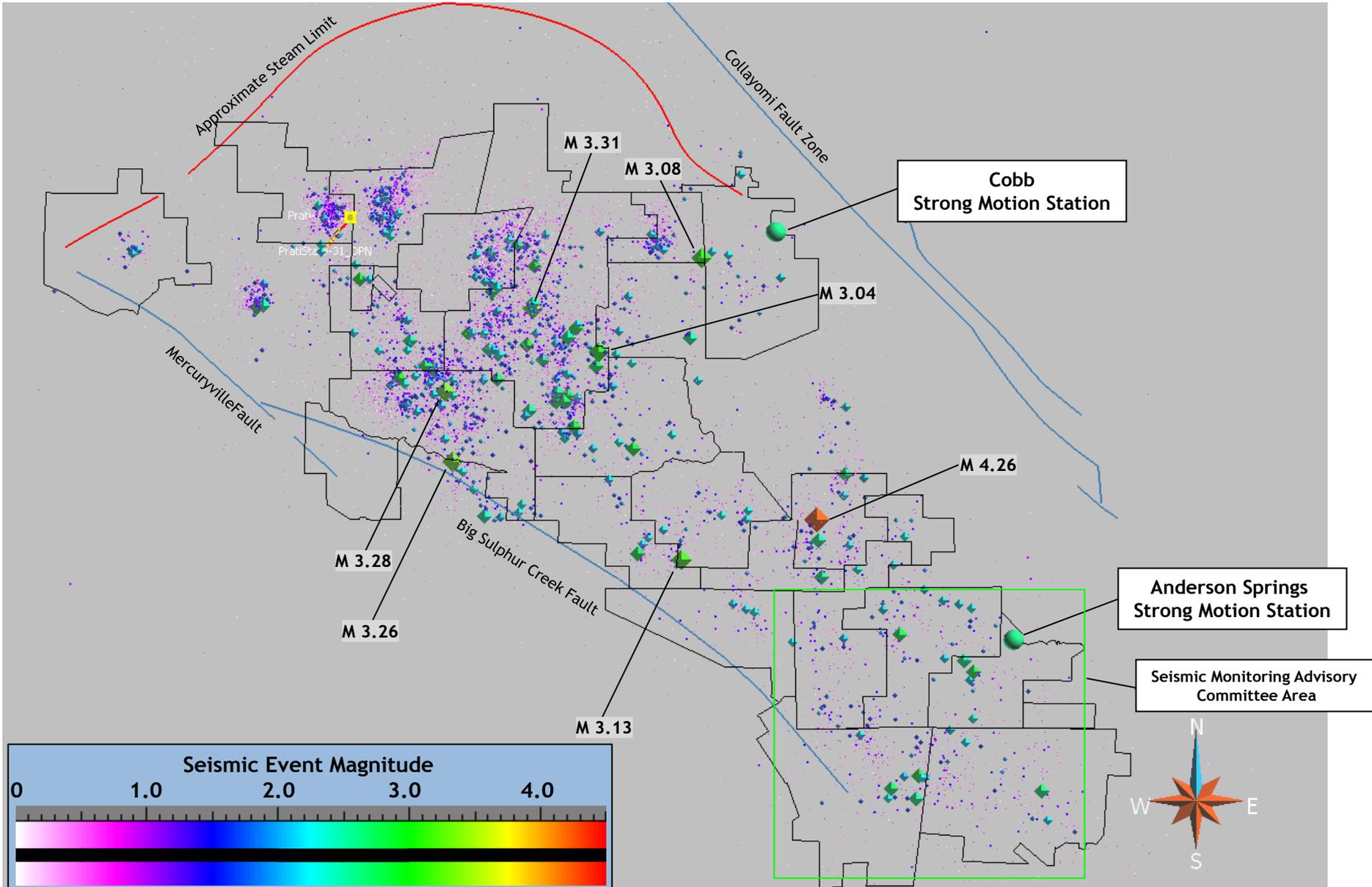
■ SRGRP ■ SEGEP ■ Fresh Water ■ Condensate

Water Injection Sources (Gallons)				
Month	SRGRP	SEGEP	Fresh Water	Condensate
October	418,080,000	132,252,000	-	303,141,049
November	504,290,000	140,555,000	-	381,016,932
December	527,520,000	137,601,000	-	357,737,901
January	523,850,000	132,710,000	25,853,018	381,323,759
February	401,180,000	123,929,000	10,075,313	376,404,572
March	320,310,000	129,949,000	113,161,535	454,024,170

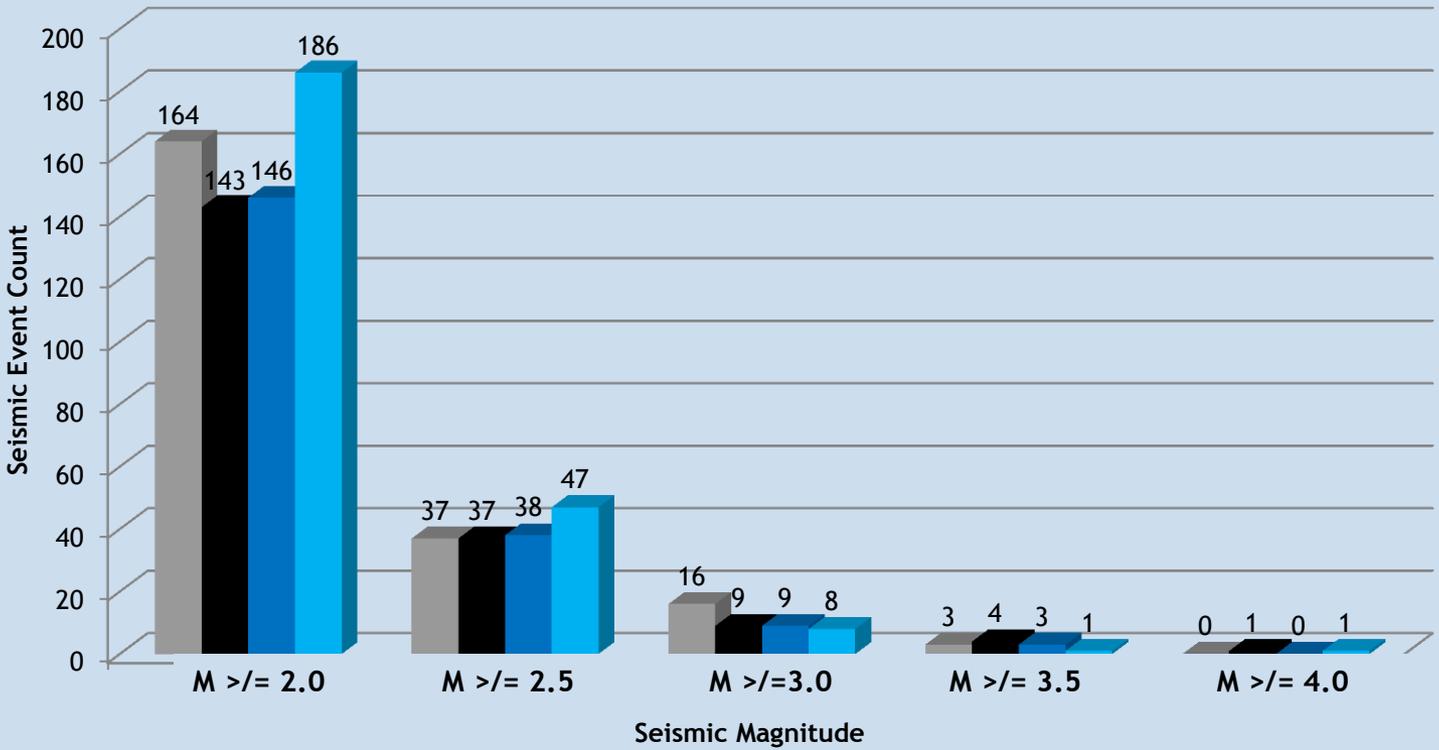
# Seismic Monitoring Advisory Committee Meeting

1 October 2011 to 31 March 2012

## Field-wide Seismicity Analysis



### Field-wide Seismicity Analysis Previous Three Periods vs. Current SMAC Reporting Period



■ 1 Apr 2010 to 31 Sep 2010 ■ 1 Oct 2010 to 31 Mar 2011 ■ 1 Apr 2011 to 31 Sep 2011 ■ 1 Oct 2011 to 31 Mar 2012

# Seismic Monitoring Advisory Committee

## Seismicity Analysis

### SRGRP Report Cross Section for 1 Sept 2011 to 29 Feb 2012



#### EARTHQUAKE-CORRELATED STRONG-MOTION TRIGGERS.

Comparison of Peak Horizontal Acceleration (PGA) incidences during three time periods:

1. Pre-SRGRP (11 July to 18 November 2003)
2. During SRGRP (19 November 2003 to 28 February 2011)
3. Most recent biannual reporting period (1 March 2011 to 31 August 2011)

Red = Previous Period #s

		MM Intensity→	I	II -- III	IV	V	VI
			PGA (g)	0.0017	0.014	0.039	0.092
Quantity	Station	Time Period	≤0.0017	to 0.014	to 0.039	to 0.092	to 0.18
Count	ADSP	Pre-SRGRP	87	207	19	4	1
Count	ADSP	During SRGRP	2689	4220	413	120	17
Count	ADSP	9/1/11-2/29/12	219	303	26	7	2
Count	COB	Pre-SRGRP	89	46	6	3	0
Count	COB	During SRGRP	3559	2049	166	31	6
Count	COB	9/1/11-2/29/12	195	99	17	1	0
Annualized Rate	ADSP	Pre-SRGRP	243	577	53	11.2	2.8
Annualized Rate#	ADSP	During SRGRP	377**	553	54	15.7	2.2
Annualized Rate&	ADSP	9/1/11-2/29/12	524 ↓ 454	553 ↑ 629	70 ↓ 54	16.4 ↓ 14.5	0.0 ↑ 4.2
Annualized Rate	COB	Pre-SRGRP	266	138	18	9.0	0.0
Annualized Rate*	COB	During SRGRP	478	275	22	4.2	0.8
Annualized Rate†	COB	9/1/11-2/29/12	604 ↓ 505	363 ↓ 256	28 ↑ 44	12.0 ↓ 2.6	0.0 = 0.0

# Accounts for ADSP station outage 20 July 2009 to 15 August 2009, 5 to 9 August 2010 and 3 to 29 June 2011.

\*\* Corrected for 1 September 2005 to 28 February 2006 when no events were recorded in this category because the ADSP trigger threshold was set at 0.002g.

& Accounts for ADSP station outage 26 to 29 December 2011 and 8 to 11 February 2012.

\* Accounts for COB station outage 10 November 2003 to 28 January 2004, 12 October 2009 to 6 November 2009, 3 to 10 February 2010 and 18 April 2010 to 3 May 2010, 7 to 10 September, 2010.

† Accounts for COB station outages 3 to 12 September 2011, 9 to 20 November 2011 and 1 to 12 December 2011.

Field-wide data for 1 Sep 2011 to 29 Feb 2012 provided by Calpine to URS Corporation

LBNL / USGS Seismicity

Strong Motion Measurements

SRGRP Well Monthly Injection Volumes

Earth Quake Hotline Reports

Draft report completed by 27 April 2012

Final report with minor Calpine/URS revisions complete by ~21 May 2012

Seismicity results consistent with Environmental Impact Report projections

Since SRGRP initiation: 50% increase in NCSN seismicity of magnitude  $\geq 1.5$

Since SRGRP initiation: no increase in NCSN seismicity of magnitude  $\geq 3.0$

Most recent seismic events of magnitude  $\geq 4.0$ :

M 4.45 05 May 2012

**M 4.26 13 February 2012 (within reporting period #17)**

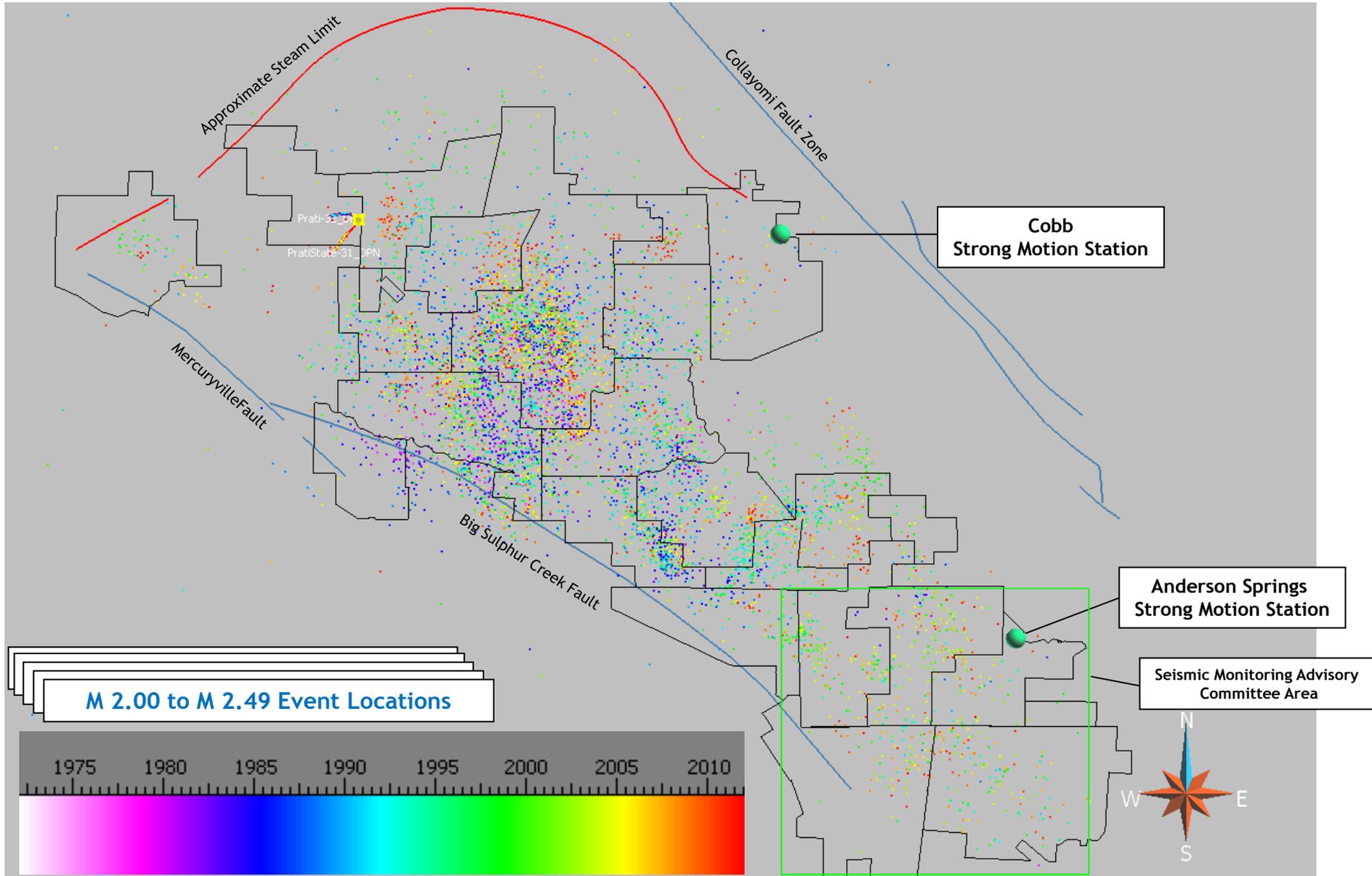
M 4.46 01 March 2011

M 4.30 04 January 2009 (two years prior)

# Seismic Monitoring Advisory Committee Meeting

## Historical Field-wide Seismicity Analysis

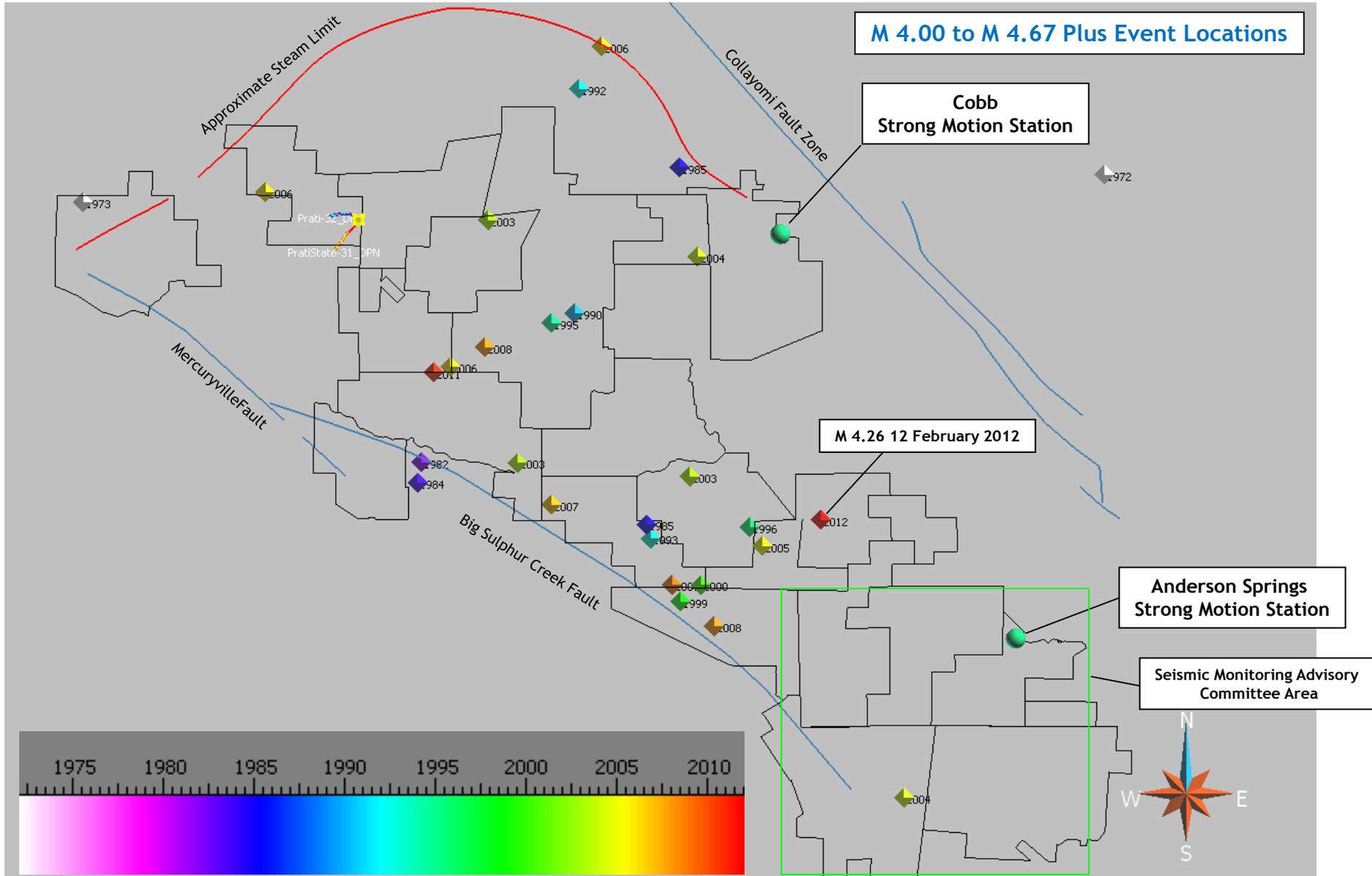
### Through 31 March 2012



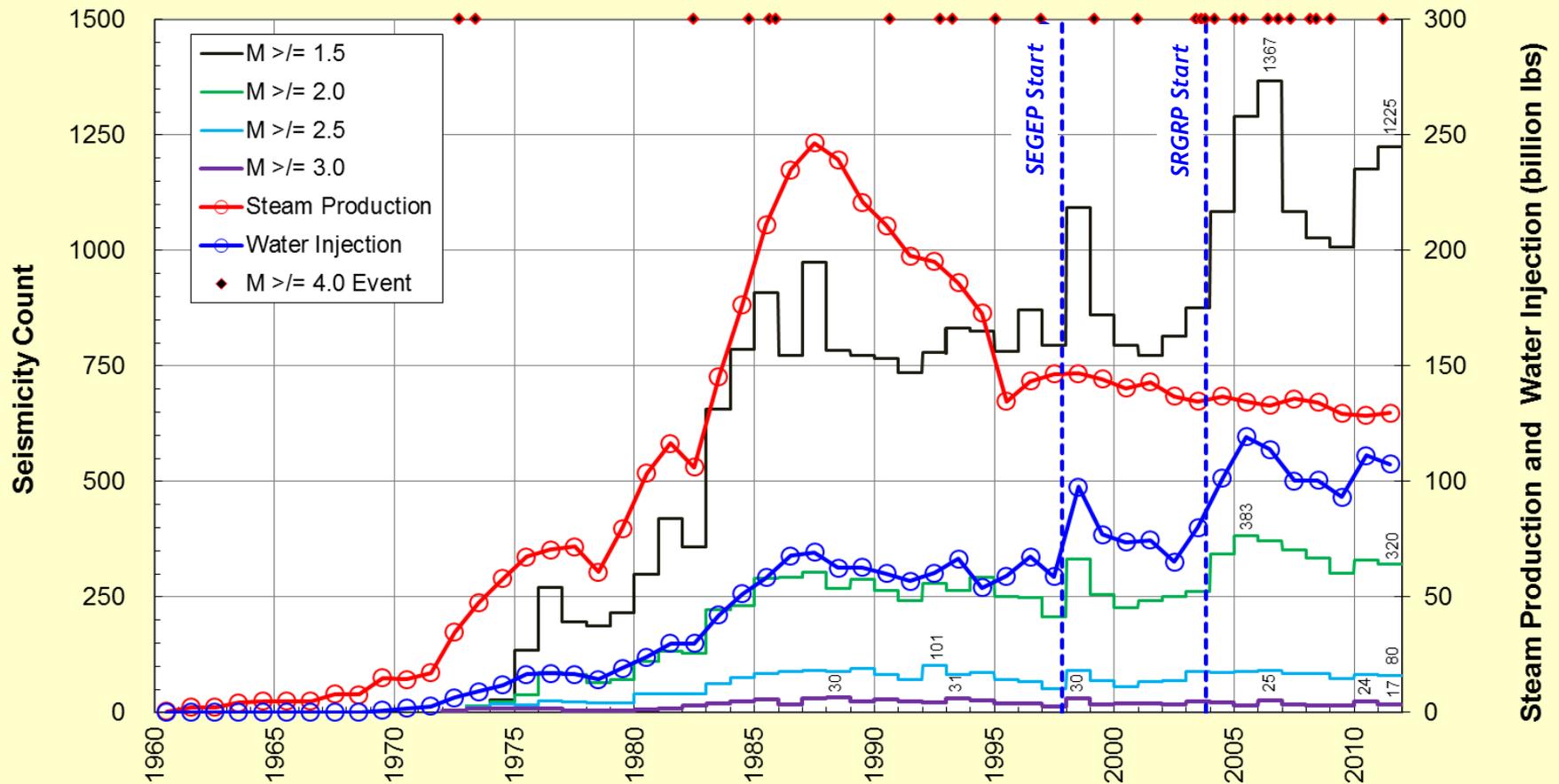
# Seismic Monitoring Advisory Committee Meeting

## Historical Field-wide Seismicity Analysis

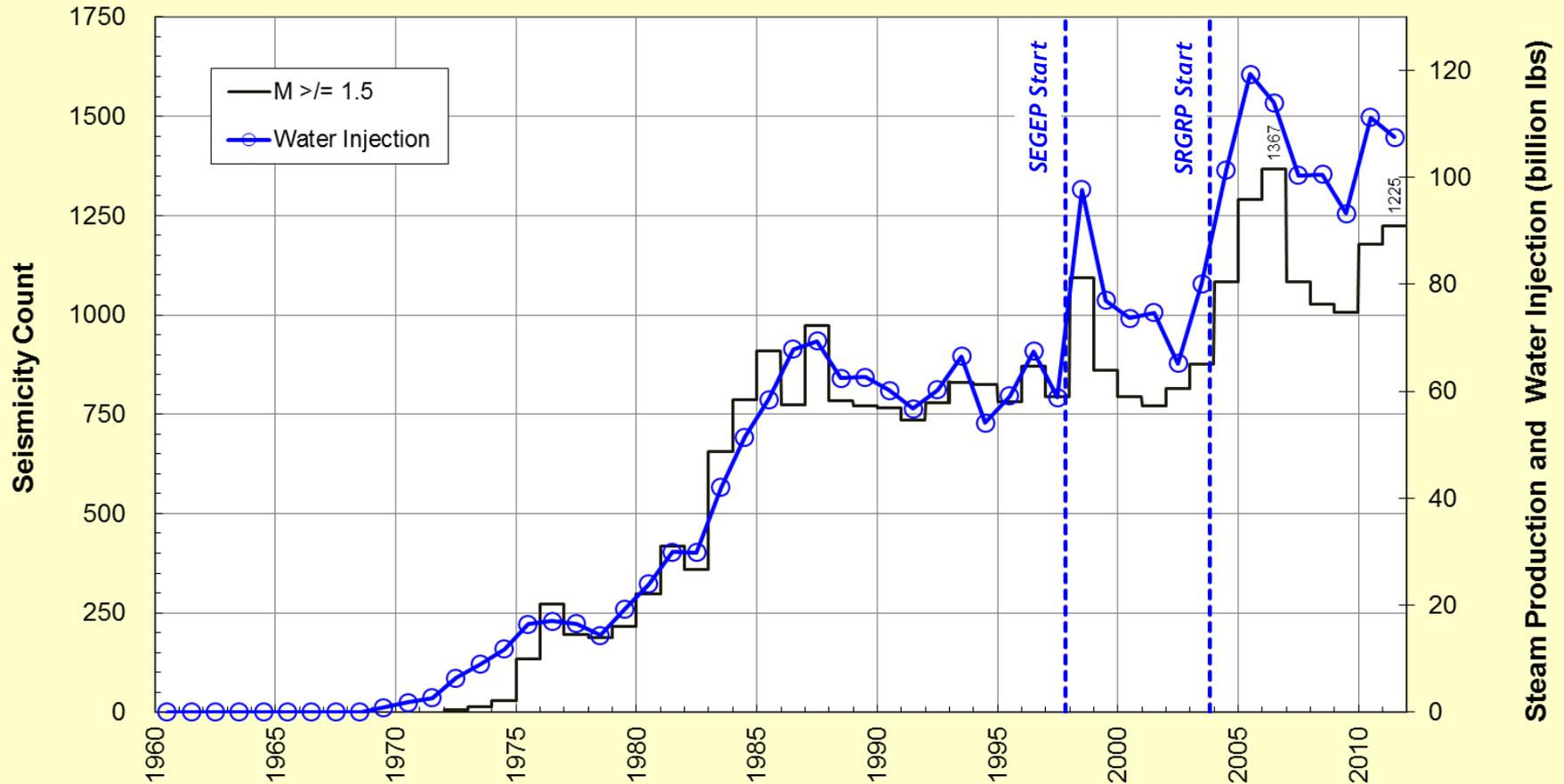
### Through 31 March 2012



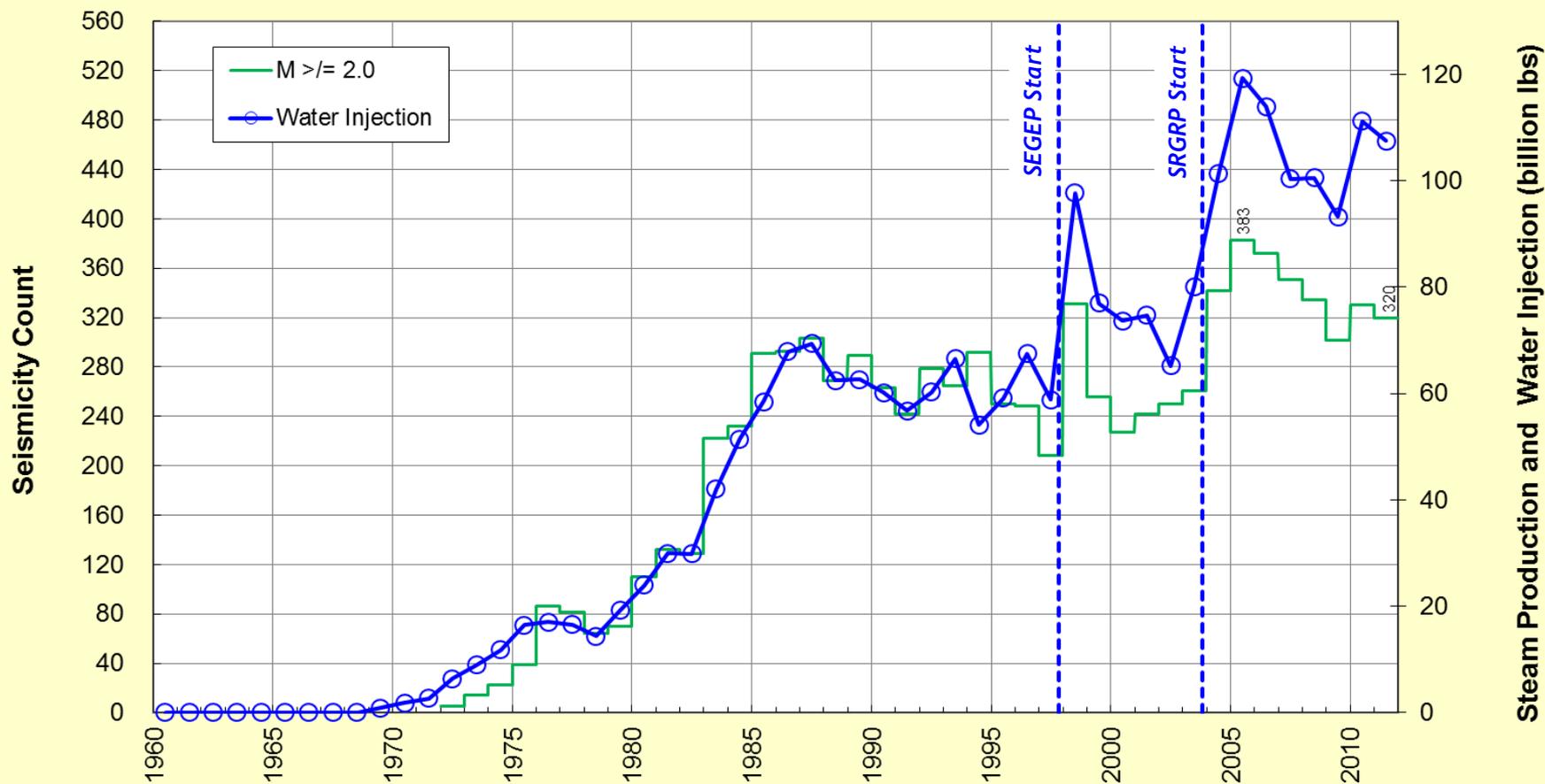
**The Geysers: Field-wide Steam Production, Water Injection and Seismicity 1960 through 2011**



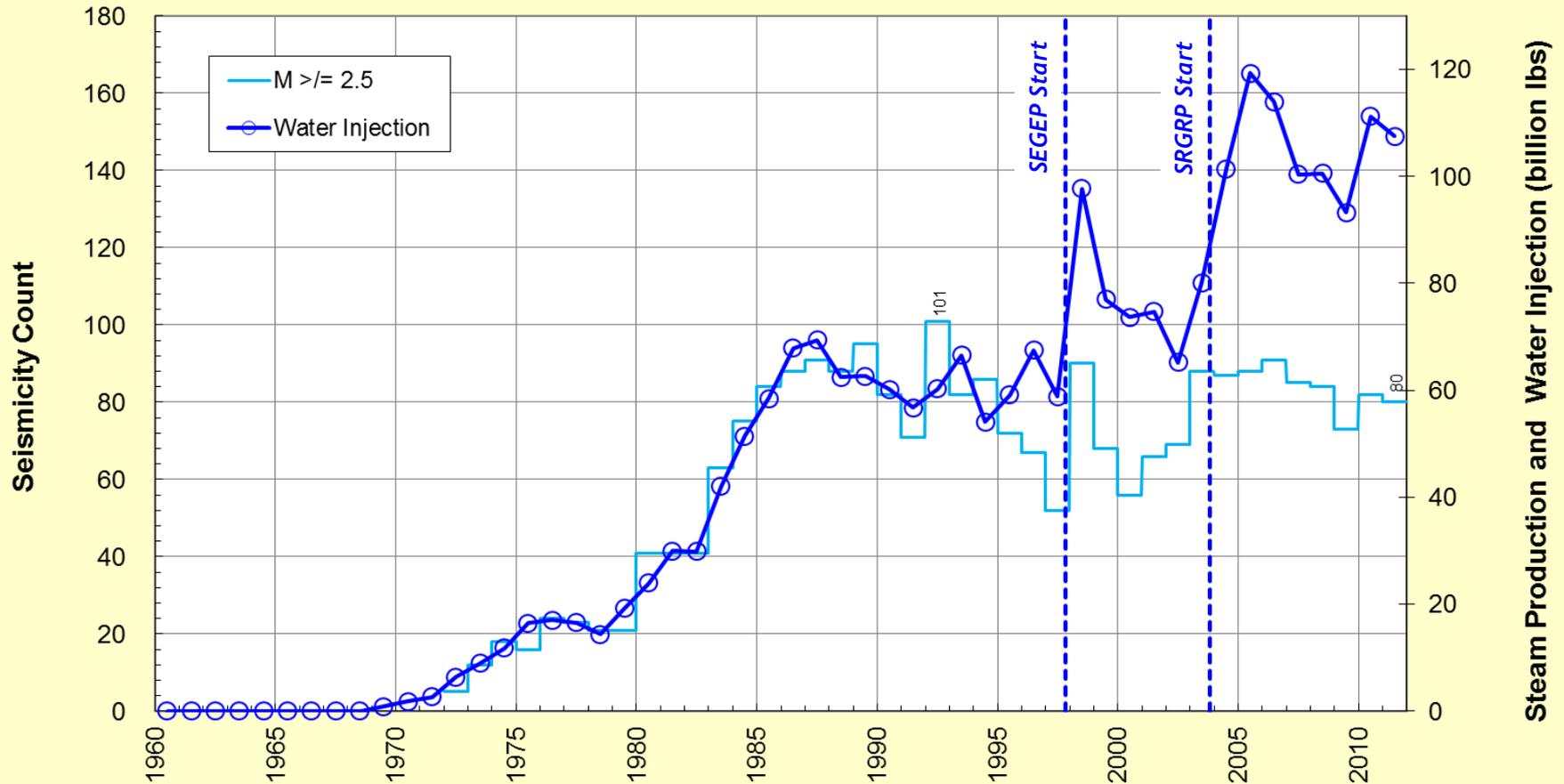
**The Geysers: Field-wide Water Injection and  $M \geq 1.5$  Seismicity  
1960 through 2011**



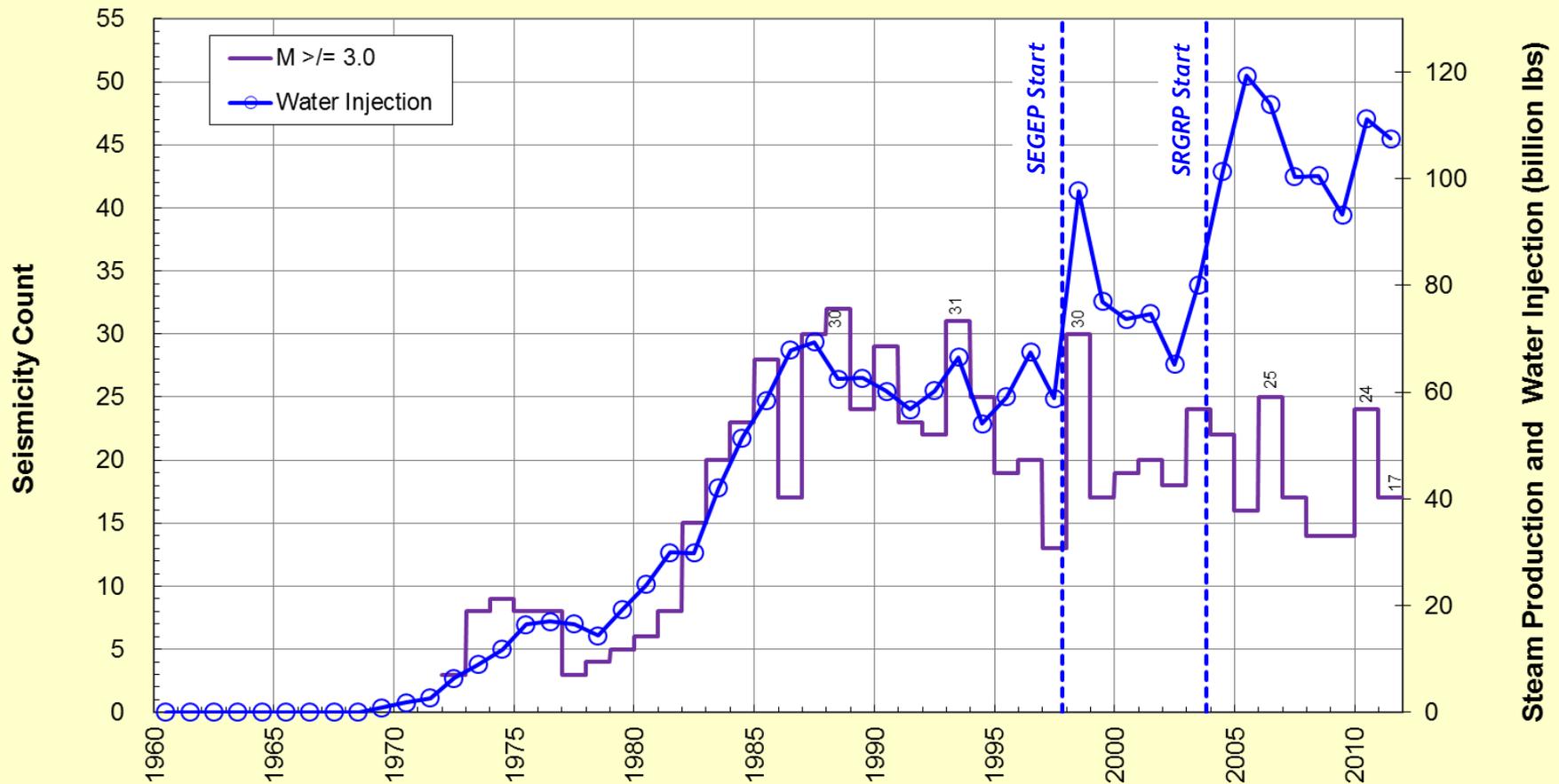
**The Geysers: Field-wide Water Injection and  $M \geq 2.0$  Seismicity  
1960 through 2011**



**The Geysers: Field-wide Water Injection and  $M \geq 2.5$  Seismicity  
1960 through 2011**



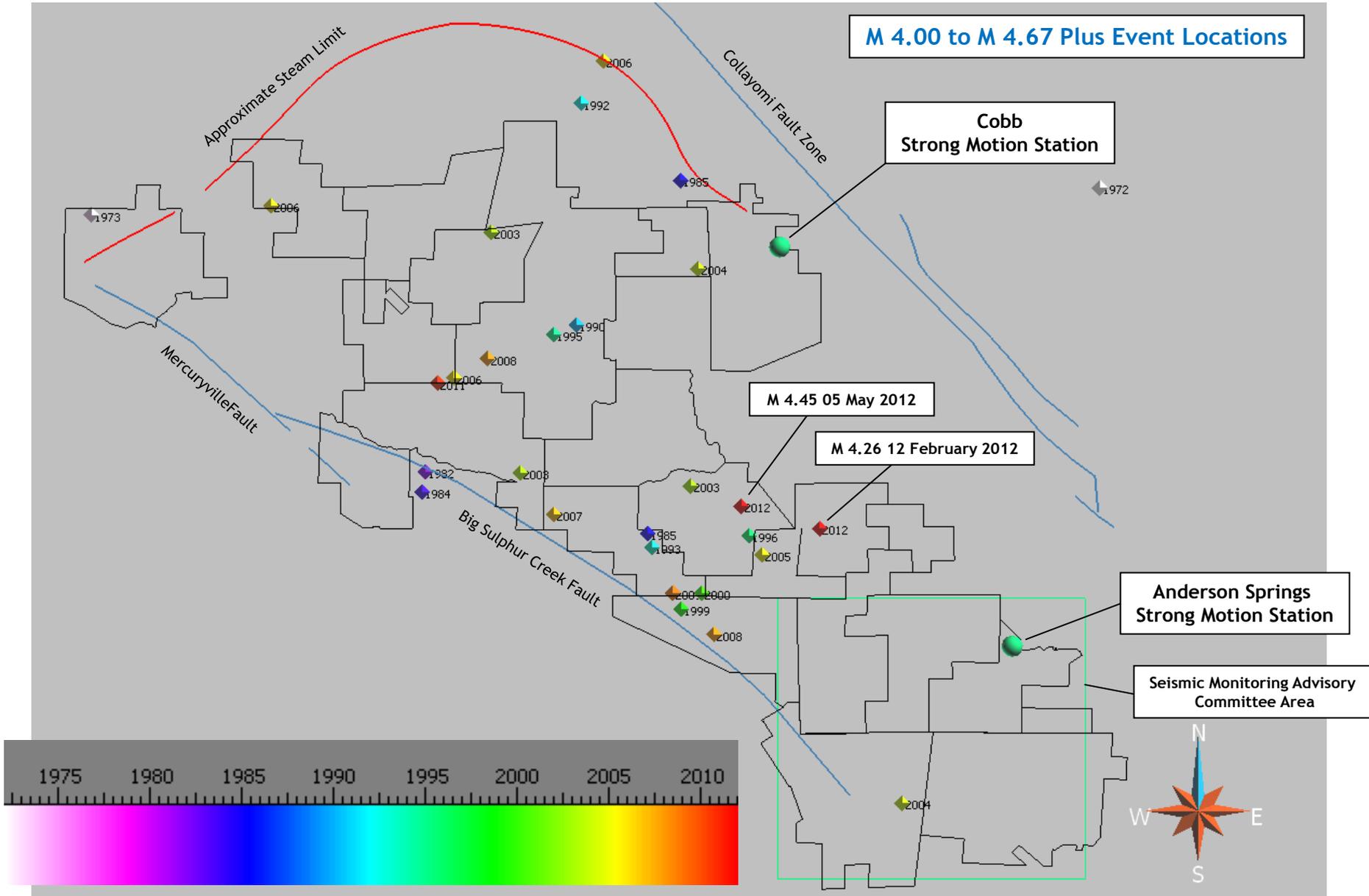
**The Geysers: Field-wide Water Injection and  $M \geq 3.0$  Seismicity  
1960 through 2011**



# Seismic Monitoring Advisory Committee Meeting

## Historical Field-wide Seismicity Analysis

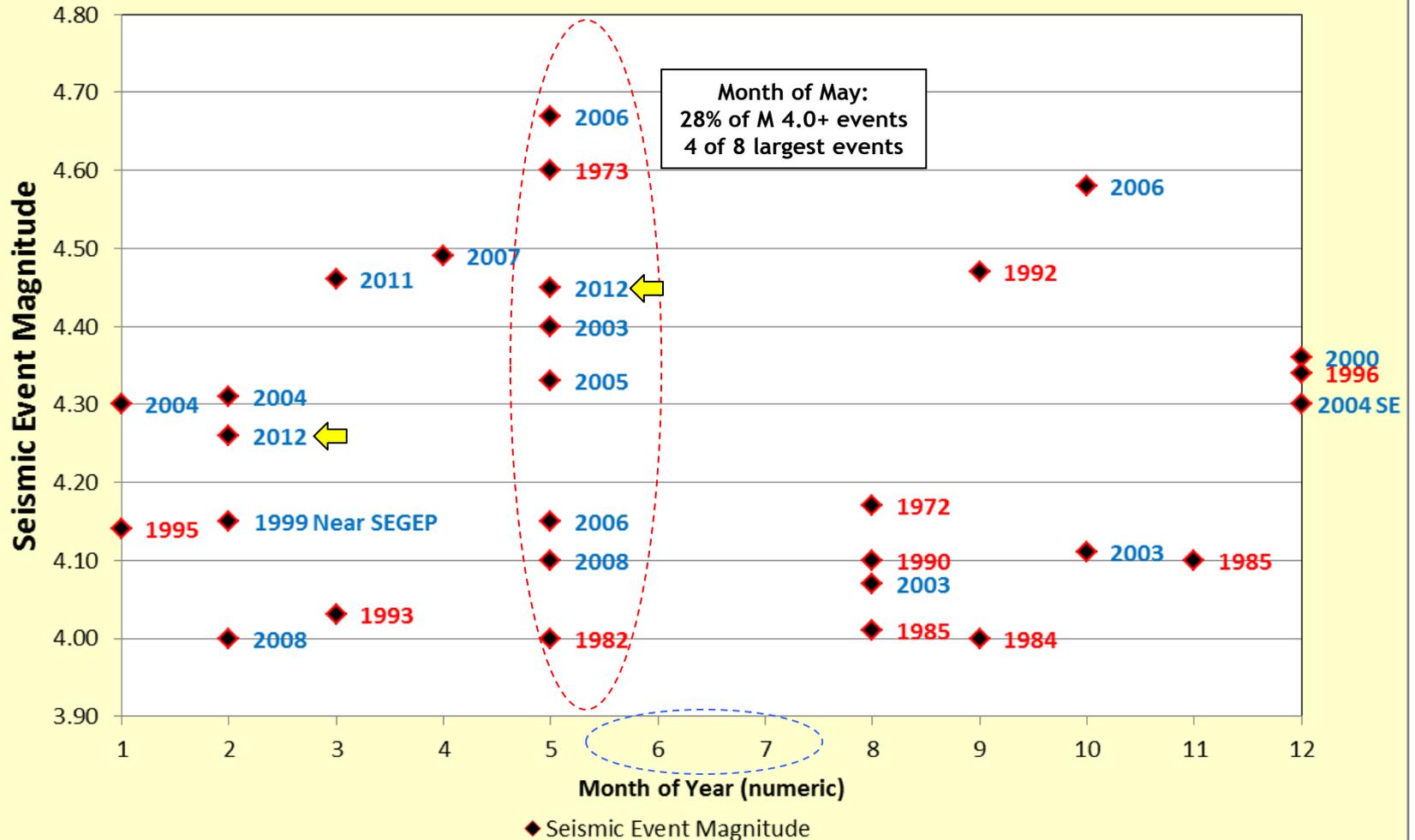
### Through 07 May 2012



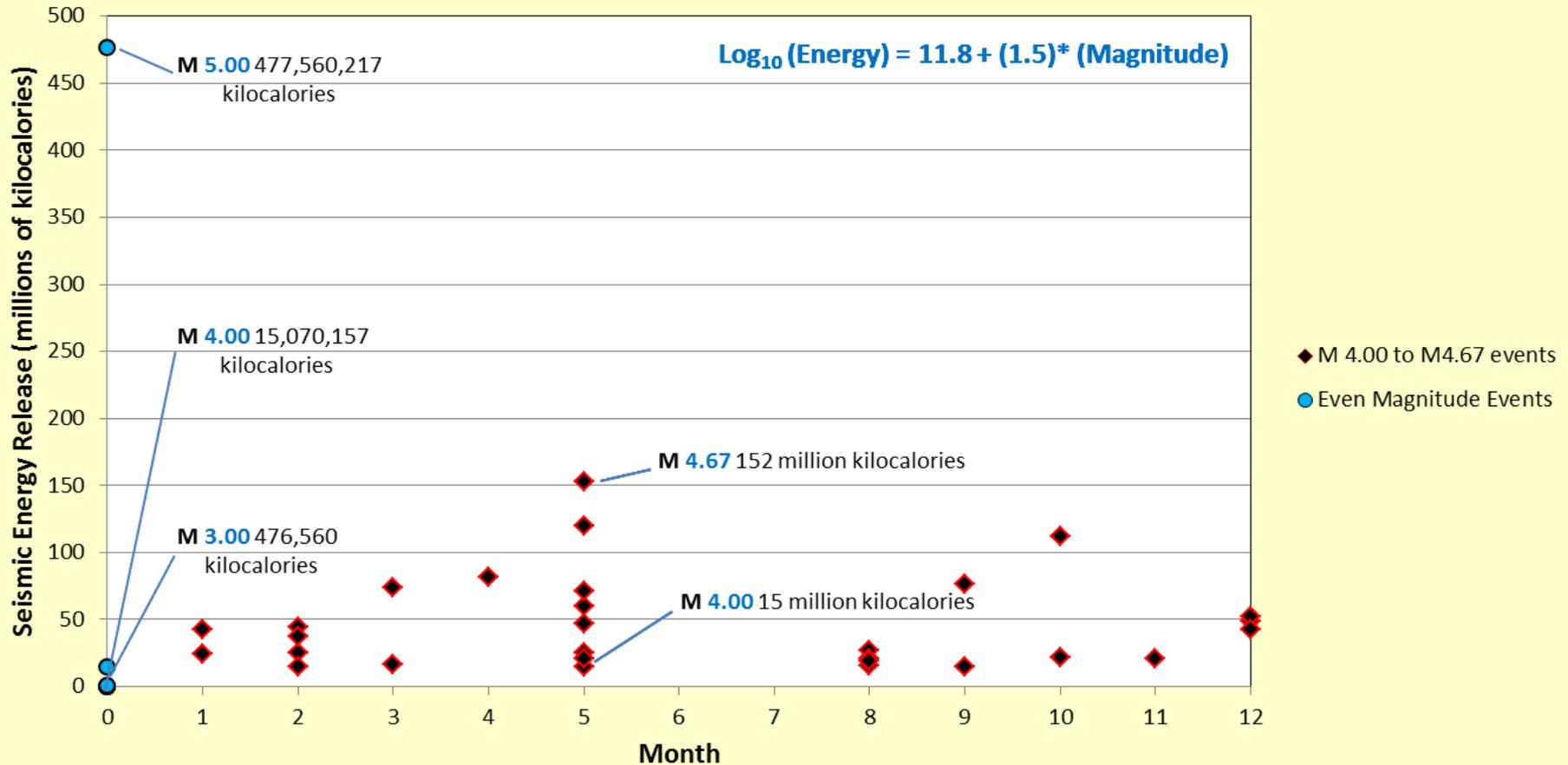
### The Geysers Seismic Events

M 4.0 or Greater; By Month (Numeric)

Red = Pre SEGEP/SRGRP; Blue = Post SEGEP/SRGRP

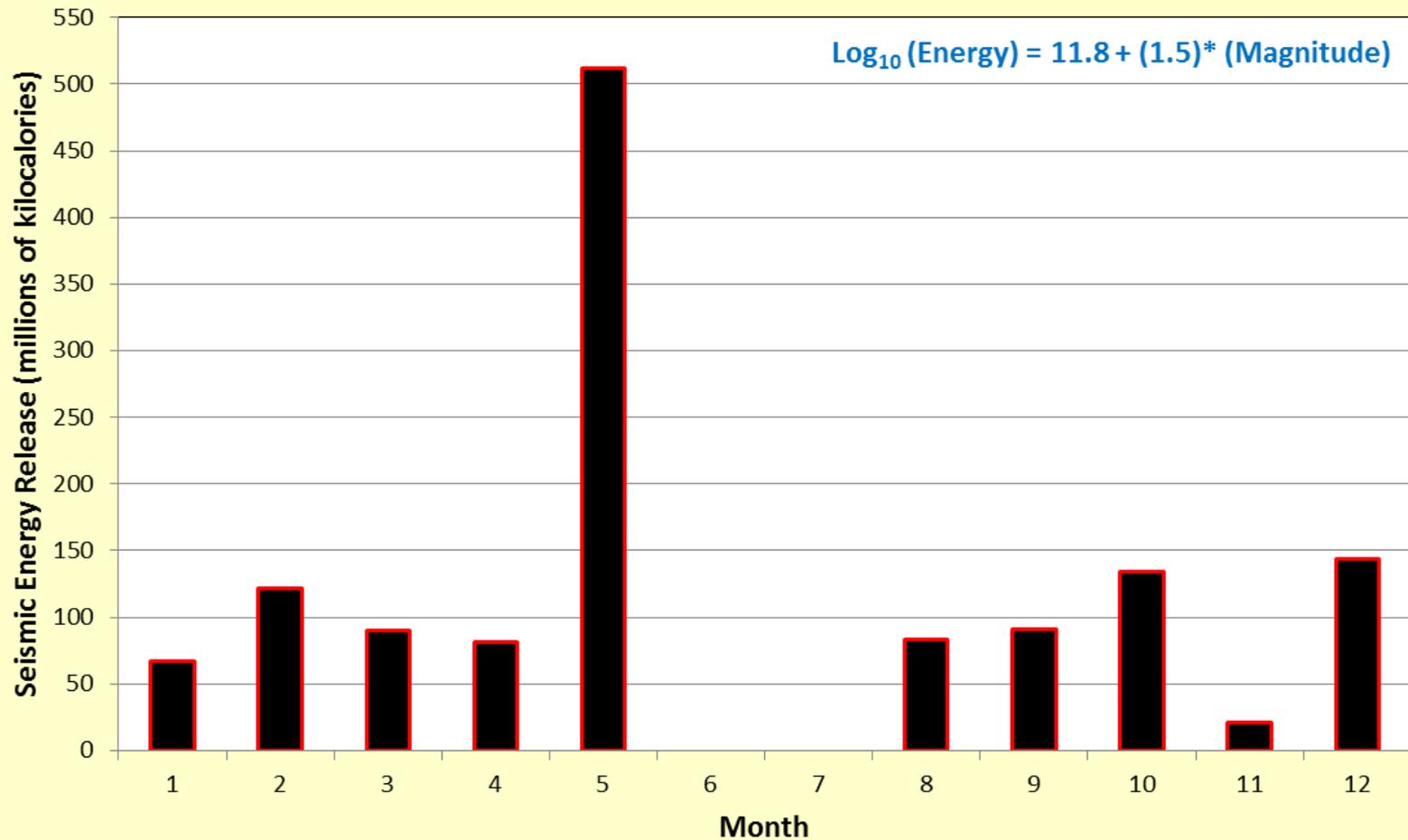


## Seismic Energy Release By Month The 29 Historical Magnitude 4.00 to 4.67 events

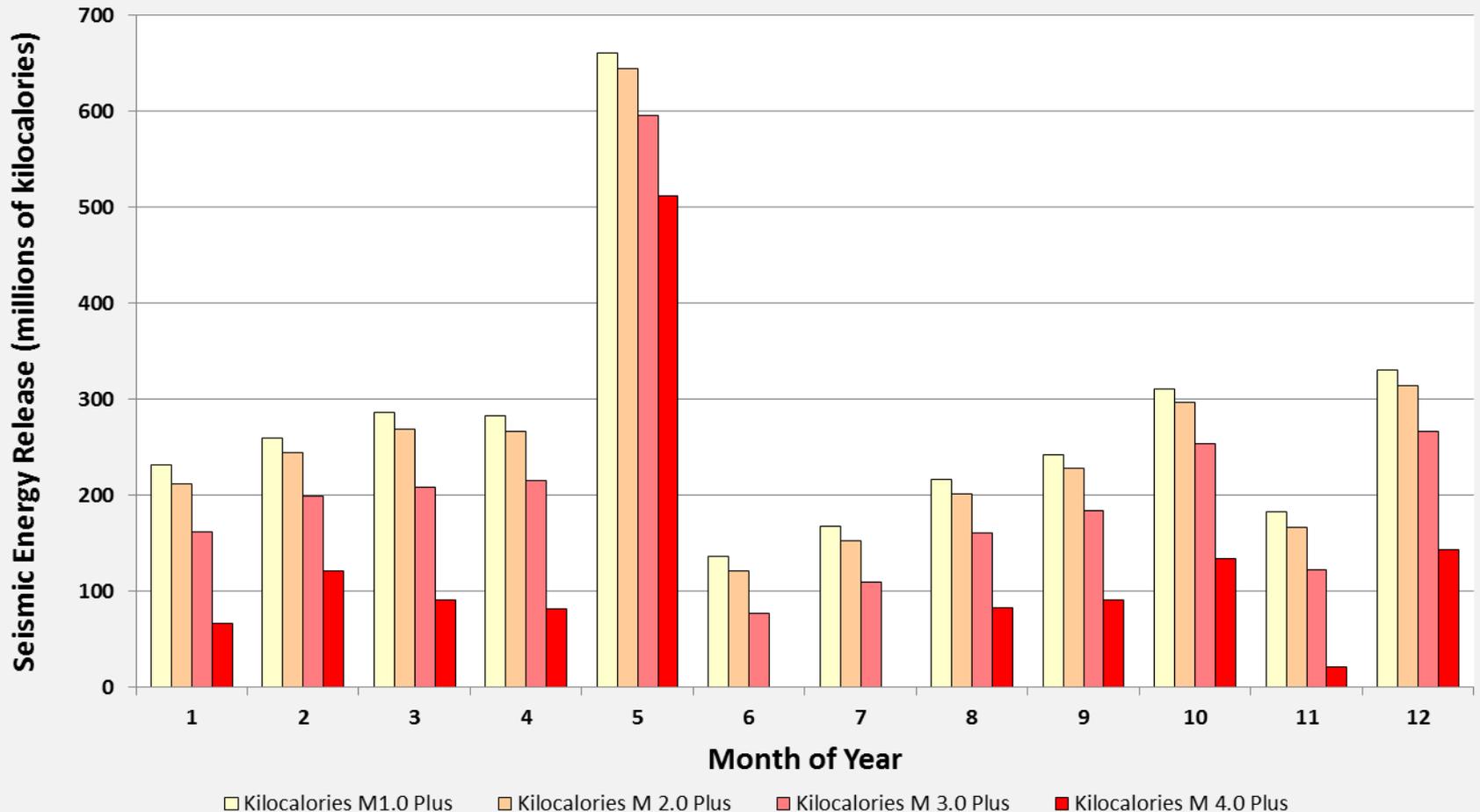


## Seismic Energy Release By Month

### Summation - 29 Historical Magnitude 4.00 to 4.67 events



### Seismic Energy Release in Kilocalories Per Month 1972 to Present For Magnitudes $\geq 1.0$ , $\geq 2.0$ , $\geq 3.0$ and $\geq 4.0$



## Seismicity ( $M \geq 4.0$ ) and Field-wide Injection Totals by Month

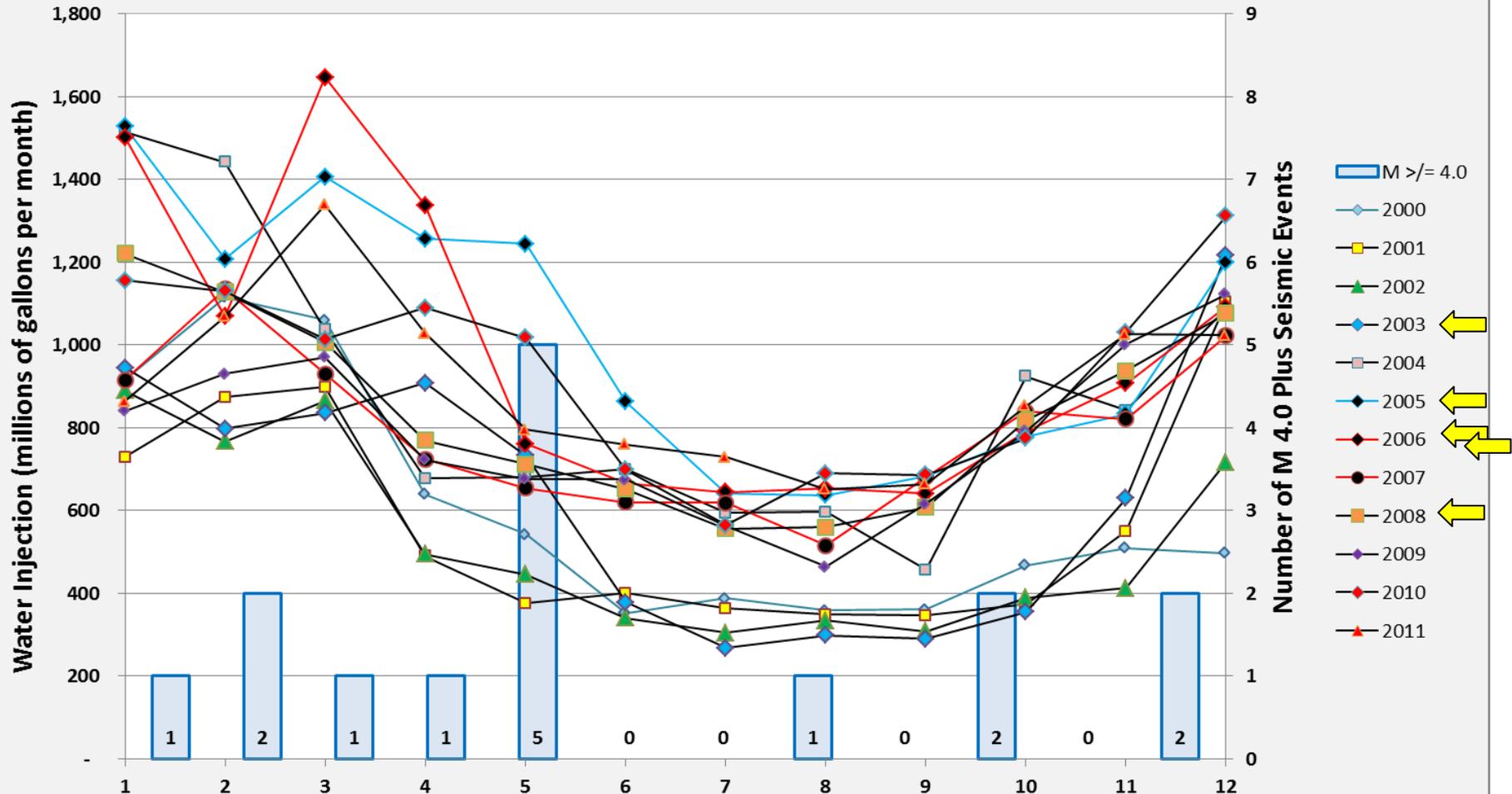
Years 2000 through 2011

SEGEP + SRGRP + Condensate + Fresh Water

$M \geq 4.0$  to  $M \leq 4.67$  Seismic Events

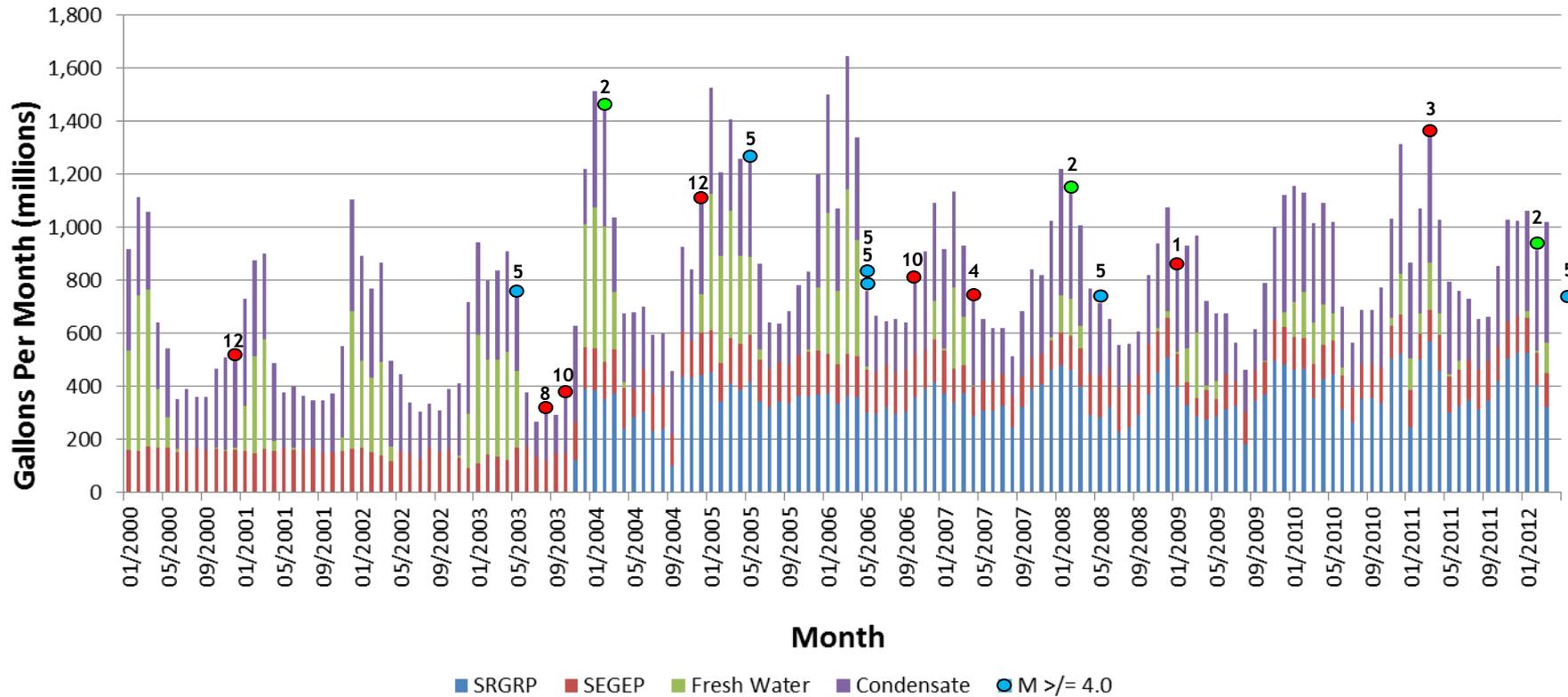
Lines: Water Injection

Bars: # of Seismic Events



M 4.00 to M 4.67 Seismic Events

### Water Injection Sources January 2000 to March 2012



Permanent Monitoring / Real-Time Processing

▼ **Lawrence Berkeley National Laboratory**  
 Installed in 2003; continued upgrades  
 31 stations; M 1.0 threshold  
 Primary Contact: Dr. Ernie Major (LBNL)

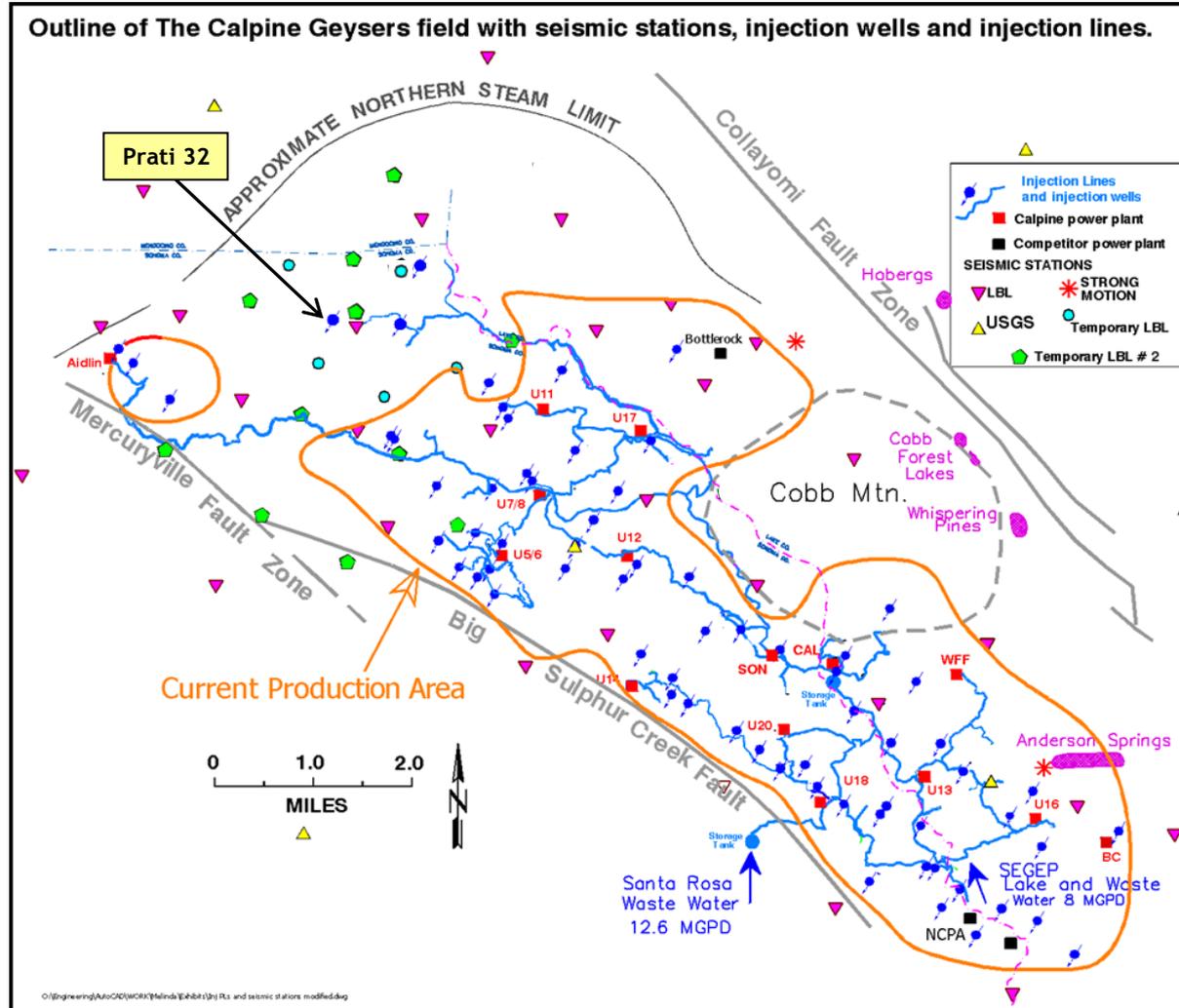
▲ **US Geological Survey**  
 Installed in 1970's; some upgrades  
 5 stations; M 1.5 threshold  
 Primary Contact: David Oppenheimer (USGS)

\* **Strong motion instruments: 3**  
 Installed in 2003; perceived shaking  
 3 stations; ~0.1% g threshold  
 Primary Contact: Jim Cullen (USGS contracted)

Project Dedicated Temporary Monitoring

● **Lawrence Berkeley National Laboratory**  
 Installed in 2010, ~ M1.0 threshold  
 5 stations; 4-6 months storage  
 Primary Contact: Dr. Ernie Major (LBNL)

◆ **Lawrence Berkeley National Laboratory**  
 Installed in 2011, ~ M1.0 threshold  
 9 stations; 3-4 weeks storage  
 Primary Contact: Dr. Lawrence Hutchings (LBNL)



Research Collaboration with European GEISER Project\*  
Coordinated through GFZ Potsdam (Germany)

**Goal:**

Address challenges to geothermal energy



GEOTHERMAL ENGINEERING  
INTEGRATING MITIGATION  
OF INDUCED SEISMICITY  
IN RESERVOIRS

**Main topics:**

1. *World-wide acquisition and analysis of induced seismicity data*
2. *Understanding induced seismicity the geomechanics and processes*
3. *Consequences of induced seismicity*
4. *Strategies for the mitigation of induced seismicity*

Triaxial Broadband Seismometer  
in Sealed Container

GÜRALP: 60 second to 50Hz  
or  
Trillium: 120 second to 100 Hz



Solar Panel on  
Triangular Frame

Action Packer with  
Digitizer and Battery

Mendocino County Line GEISER Seismic Monitoring Station



Trillium triaxial  
seismometer

\* GEISER Partners: GFZ Potsdam, BRGM, ISOR, TNO, ETHZ, STATOIL, GEOWATT, NORSAR, ARMINES, EOST, KNMI, AMRA, INGV

## Research Collaboration with European GEISER Project Coordinated with Dr. Roland Gritto; Array Information Technology

### At The Geysers:

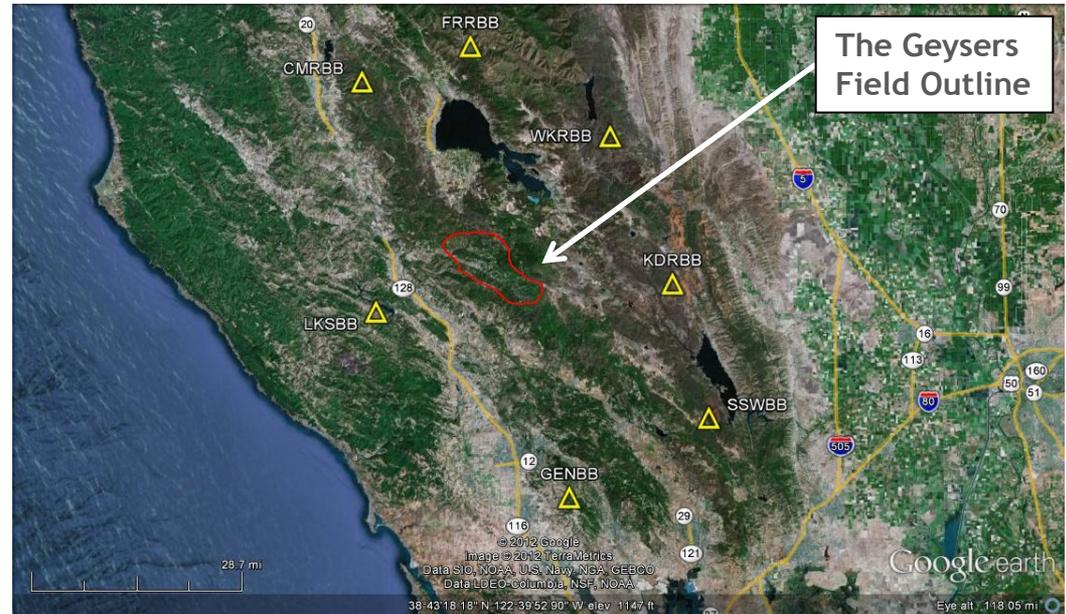
- 32 stations installed in early 2012:
  - 25 within field boundary
  - 7 beyond field boundary
- Continuous monitoring
  - Broadband
  - Within and beyond geothermal field

### Most are co-located:

- LBNL Stations (24)
- USGS Stations (4)
- Strong Motion Stations (1)

### Improve understanding of:

- structural features
- seismic energy attenuation
- seismic velocities ( $V_p$  and  $V_s$ )
- velocity change with reservoir fluid variations



**GEISER**

GEOTHERMAL ENGINEERING  
INTEGRATING MITIGATION  
OF INDUCED SEISMICITY  
IN RESERVOIRS

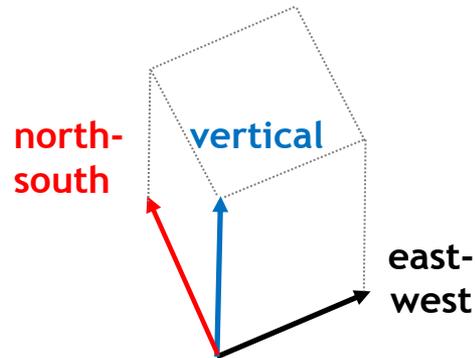
This seismic monitoring network contributes to worldwide GEISER consortium goals

Research Project with United States Geological Survey

Primary Contact: Dr. David Oppenheimer

#### Traditional orthogonal seismometers

- record three components of linear motion



#### Next generation “rotational” sensors

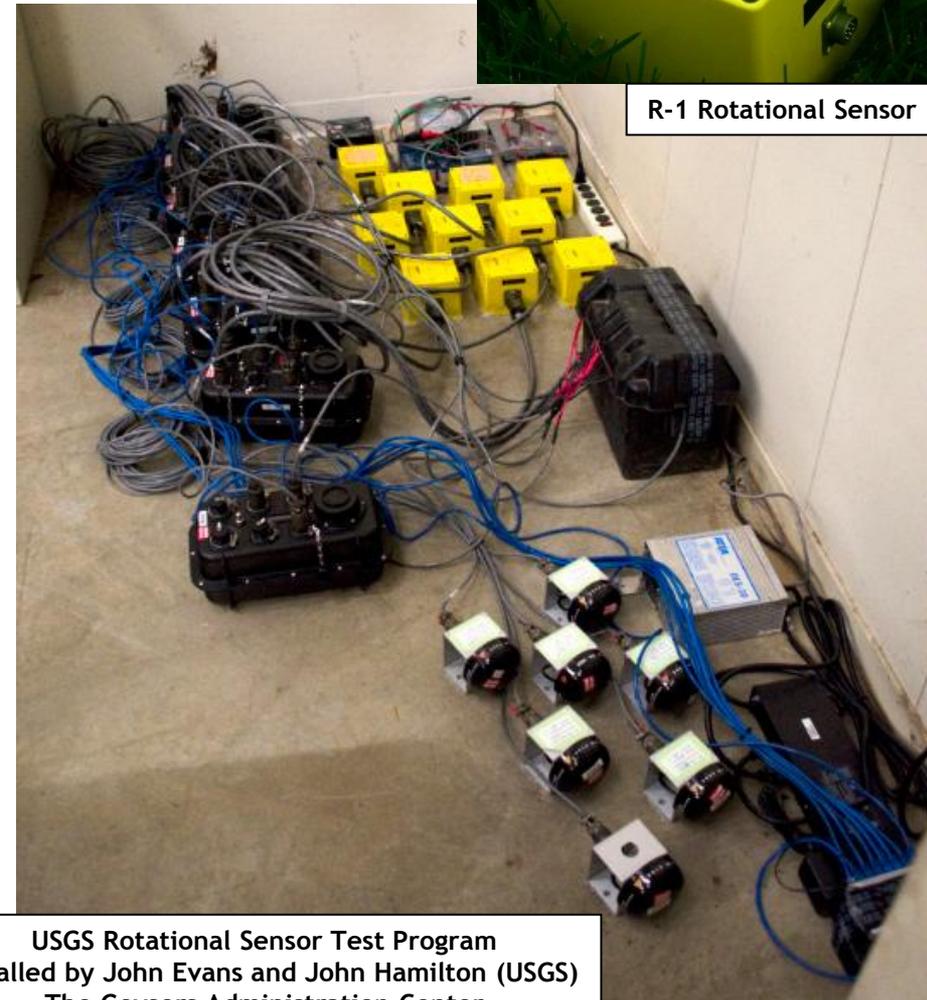
- record six components of motion (6DOF)
- three linear + three rotational
- important for larger events involving tilt
- more faithfully recover the true ground motion

#### Installed 03 May 2012

- 10 *eentec Services* rotational seismometers
- 1 traditional accelerometer
- 7 dataloggers
- 7 GPS repeaters and GPS antenna (event timing)
- Real-time data recovery - USGS network



R-1 Rotational Sensor



USGS Rotational Sensor Test Program  
Installed by John Evans and John Hamilton (USGS)  
The Geysers Administration Center

## Better distribution; more uniform injection rates

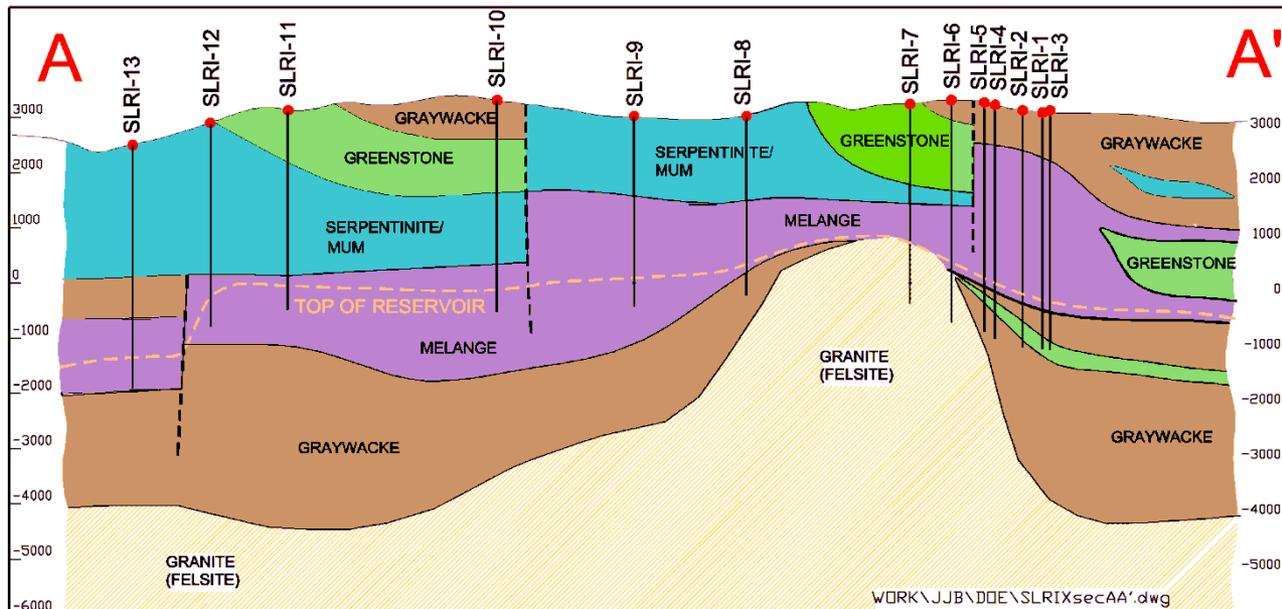
Lower injection rates per well being evaluated  
(e.g. 500 gallons per minute; 0.72 million gallons/day)

Minimization of injection rate variability (individual well and field-wide)

Shifting injection towards northwest and away from communities

Distributed injection, particularly near surrounding communities

Shallow low rate injector (SLRI) wells



Planned shallow, slim hole, low rate injection wells ("SLRI's). Small diameter completions to be drilled only into the upper part of the reservoir. Injection rates to be limited to  $\leq 200$  gpm.

**Voicemail Hotline (877) 4-GEYSER**

Calls transcribed and reviewed weekly since 12/16/2003

Compared with strong-motion measurements for Cobb and Anderson Springs stations

**Detailed Reporting of Events of  $M \geq 4.0$  (or  $M \geq 3.5$ ;  $MMI \geq 5$ ;  $PGA \geq 3.9\%$ )**

Provided to Calpine employees, community leaders, industry and academic representatives

**Biannual Reporting to the City of Santa Rosa**

SRGRP injection and seismicity relationships

URS Corporation geophysicists perform independent data analysis and report generation

**Biannual Meeting with Seismic Monitoring and Advisory Committee**

Field activity and seismicity update to community leaders, industry and academic representatives

**Geothermal Visitors Center**

Wednesday - Saturday

Expansion to include Enhanced Geothermal System (EGS) exhibits

**Geysers Field Tours**

Free group tours approximately monthly spring through fall ([www.geysers.com](http://www.geysers.com))

**Community Newsletter**

2-3 publications yearly by email and posted to [www.geysers.com](http://www.geysers.com)

**Northwest Geysers ENHANCED GEOTHERMAL SYSTEM Demonstration Community Updates**

18 August 2011; 04 November 2011; 14 July 2012

