



America's Premier Competitive Power Company  
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## Seismic Monitoring Advisory Committee Meeting

01 October 2017 to 31 March 2018 Reporting Period

*Calpine Geothermal Visitors Center*

*Middletown, California*

*14 May 2018*

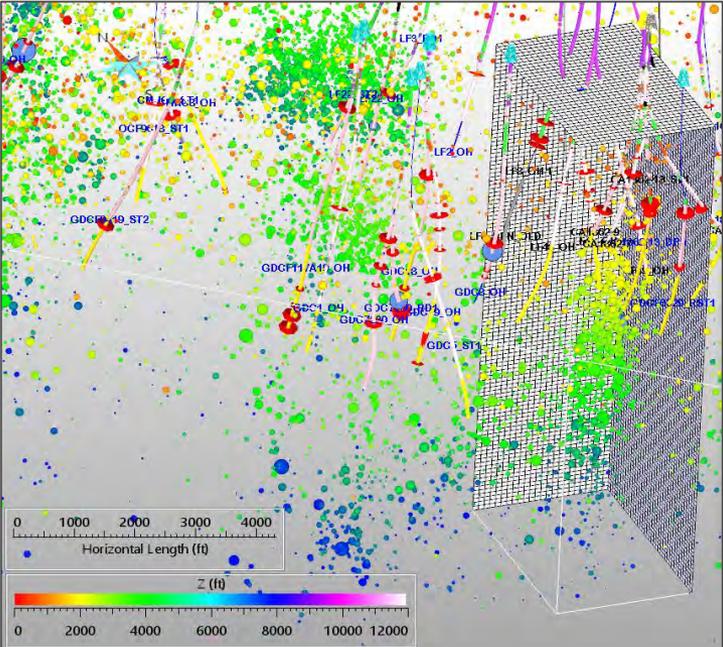
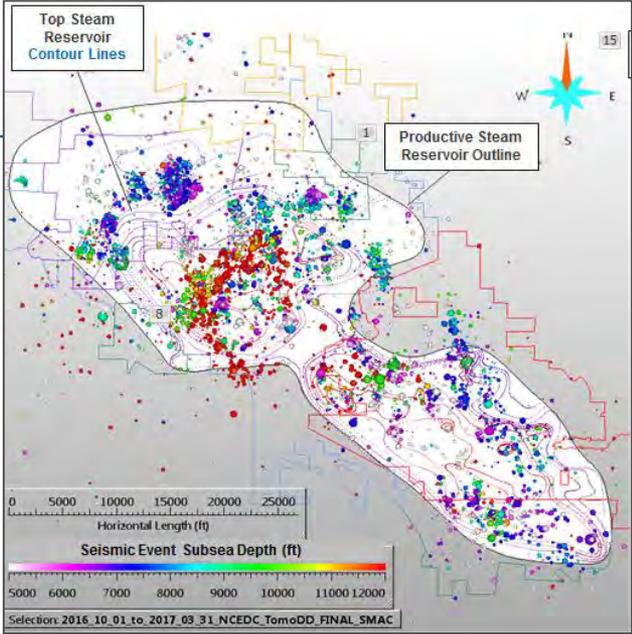
*Craig Hartline Senior Geophysicist Calpine Corporation The Geysers*

# Seismic Monitoring Advisory Committee Meeting

## Calpine Presentation Agenda

Reporting Period: 01 October 2017 to 31 March 2018

- **Status of Seismic Monitoring Networks**
  - LBNL Seismic Monitoring Network
  - USGS / Northern California Seismic Network
  - Strong Motion Stations
- **Fieldwide Seismicity Analysis**
- **Yearly Field-wide Water Injection and Seismicity**
- **Synchronized Fieldwide Water Injection and Seismicity Analysis**
- **Community Hotline**
- **Strong Motion Analysis**
- **3D Structural Model Building**
  - Fault/Fracture Analysis
  - Compartmentalization
- **Additional Seismic Monitoring and Research**



# Seismic Monitoring Advisory Committee Meeting

## Status of Seismic Monitoring Networks

### LBNL Seismic Monitoring Network

- Fully Functional

### USGS / Northern California Seismic Network

- Fully Functional

### Strong Motion Stations

- Anderson Springs

#### Community Center Strong Motion ADS2

Communications / SIM\* card failure in early February.

Reported by Calpine and repaired by USGS (John Hamilton).

Now fully functional with data gap from 03 February 2018 to 03 May 2018.

Database at: [ftp://ehzftp.wr.usgs.gov/luetgert/calpine/sm\\_sum.txt](ftp://ehzftp.wr.usgs.gov/luetgert/calpine/sm_sum.txt)

- Anderson Springs

#### Engels Strong Motion ESM

Nanometrics Titan three-component accelerometer installed September 2017.

Solar power with batteries; radio telemetry communication to LBNL seismic monitoring network.

- Cobb

#### Alder Creek Strong Motion ASM

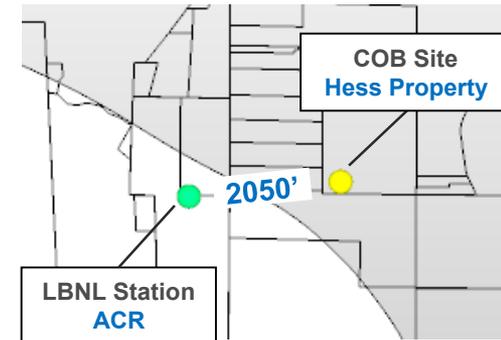
Nanometrics Titan three-component accelerometer installed May 2018 by Ramsey Haught.

Location ACR is ~2050' west-southwest of COB station on Hess property.

Solar power with batteries; radio telemetry communication to LBNL seismic monitoring network.



Alder Creek Strong Motion ASM

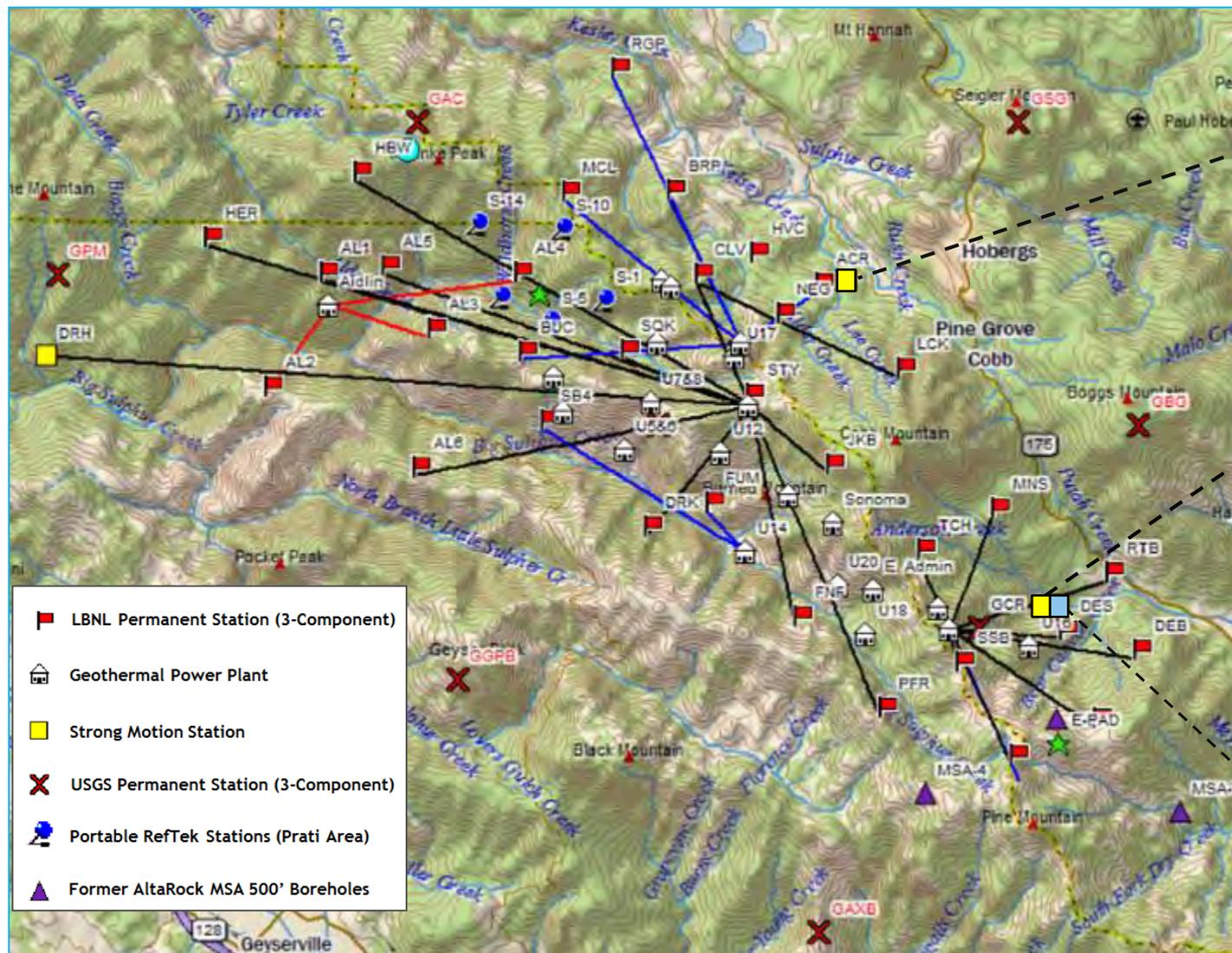


\*Subscriber Identification Module

# Seismic Monitoring Advisory Committee Meeting

## Status of Seismic Monitoring Networks

### Integration of Nanometrics Titan Accelerometers into LBNL Network



Cobb  
ASM  
Strong Motion  
At LBNL ACR Site  
~2050' WSW of Hess COB Site

LBNL

Nanometrics Titan  
Solar Power and Radio Telemetry  
May 2018

Anderson Springs  
ESM  
Strong Motion  
Engels Property

LBNL

Nanometrics Titan  
Solar Power and Radio Telemetry  
September 2017

Anderson Springs  
ADS2  
Strong Motion  
Community Center

USGS

ETNA  
Rural AC Power  
Rural Communication  
(phone line)  
January 2016

# Seismic Monitoring Advisory Committee Meeting

## Field-wide Seismicity Analysis

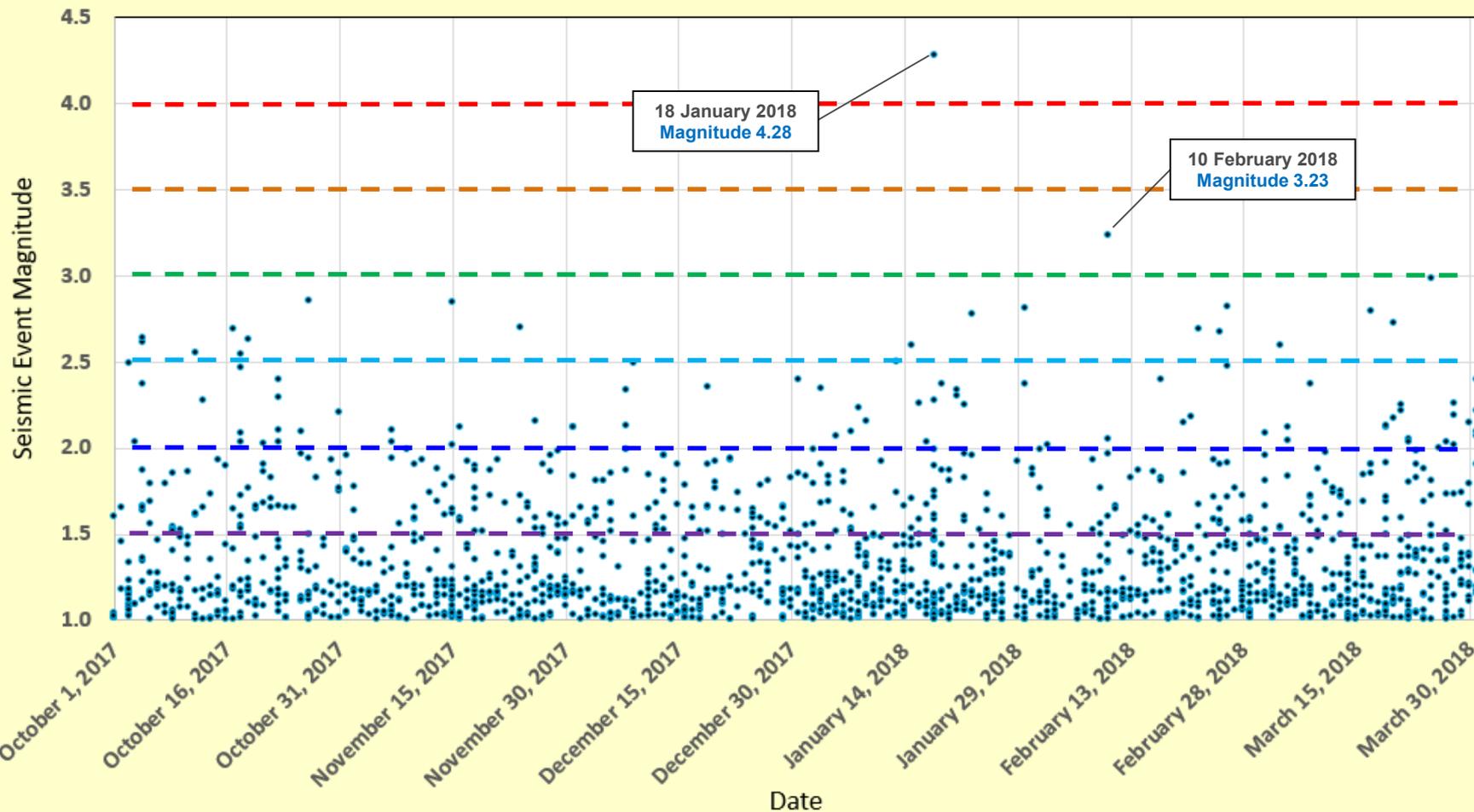
01 October 2017 to 31 March 2018

Magnitude	Number of Events
≥ 4.0	1
≥ 3.5	1
≥ 3.0	2
≥ 2.5	20
≥ 2.0	66
≥ 1.5	400

### The Geysers Fieldwide Seismicity

01 October 2017 to 31 March 2018

Magnitude ≥ 1.0

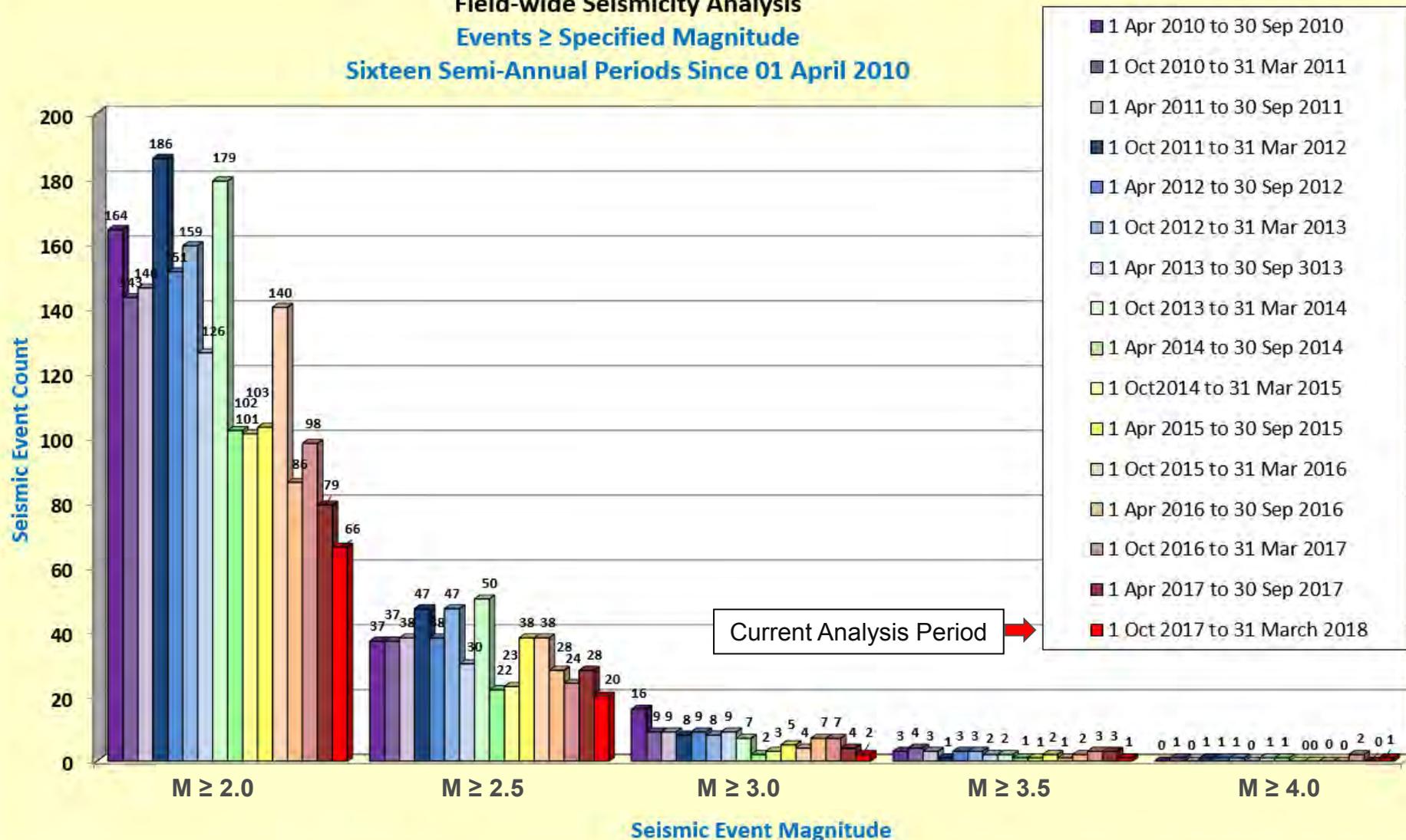


# Seismic Monitoring Advisory Committee Meeting

## Field-wide Seismicity Analysis

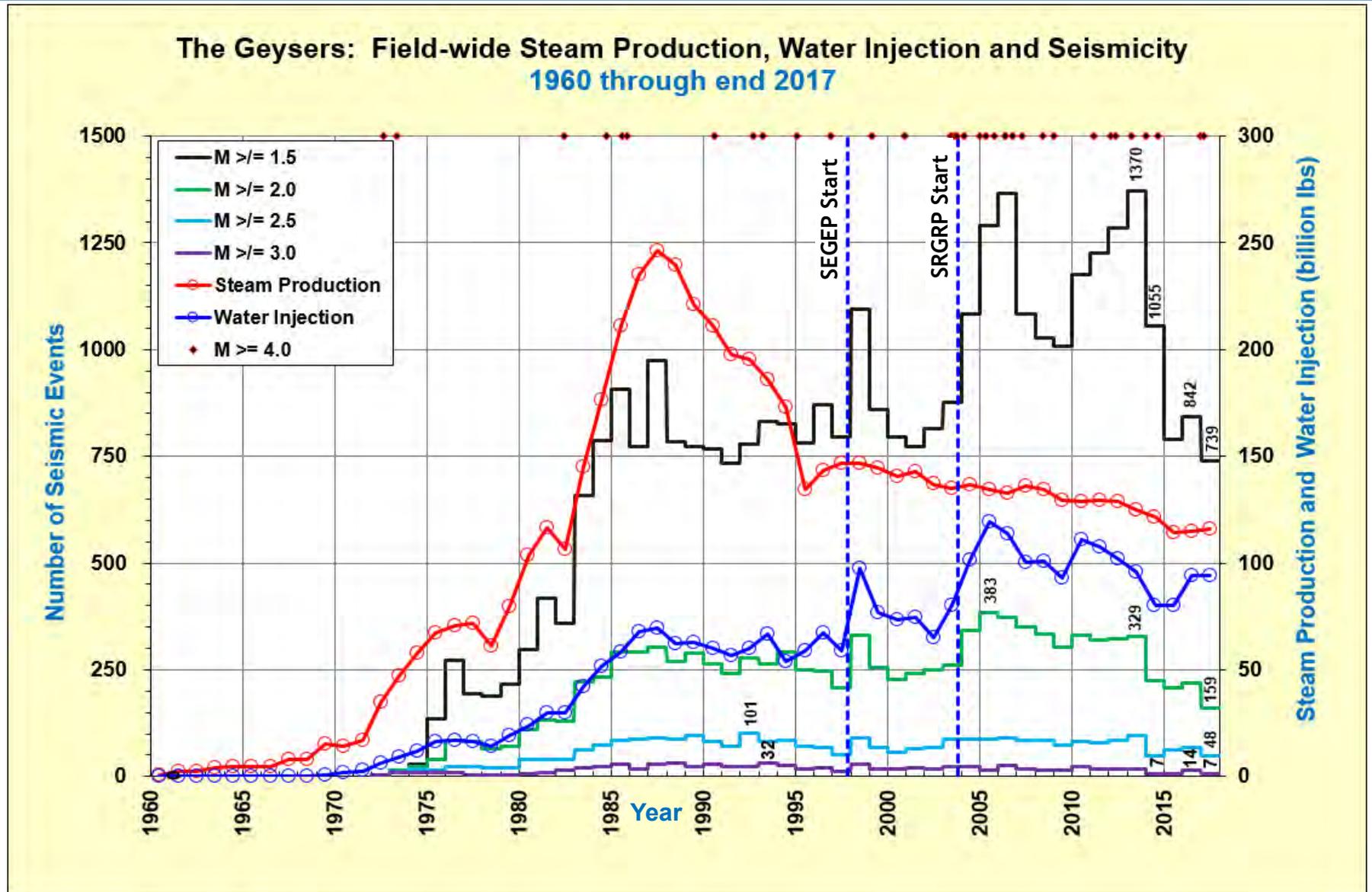
### Comparison of Sixteen Semi-annual Reporting Periods

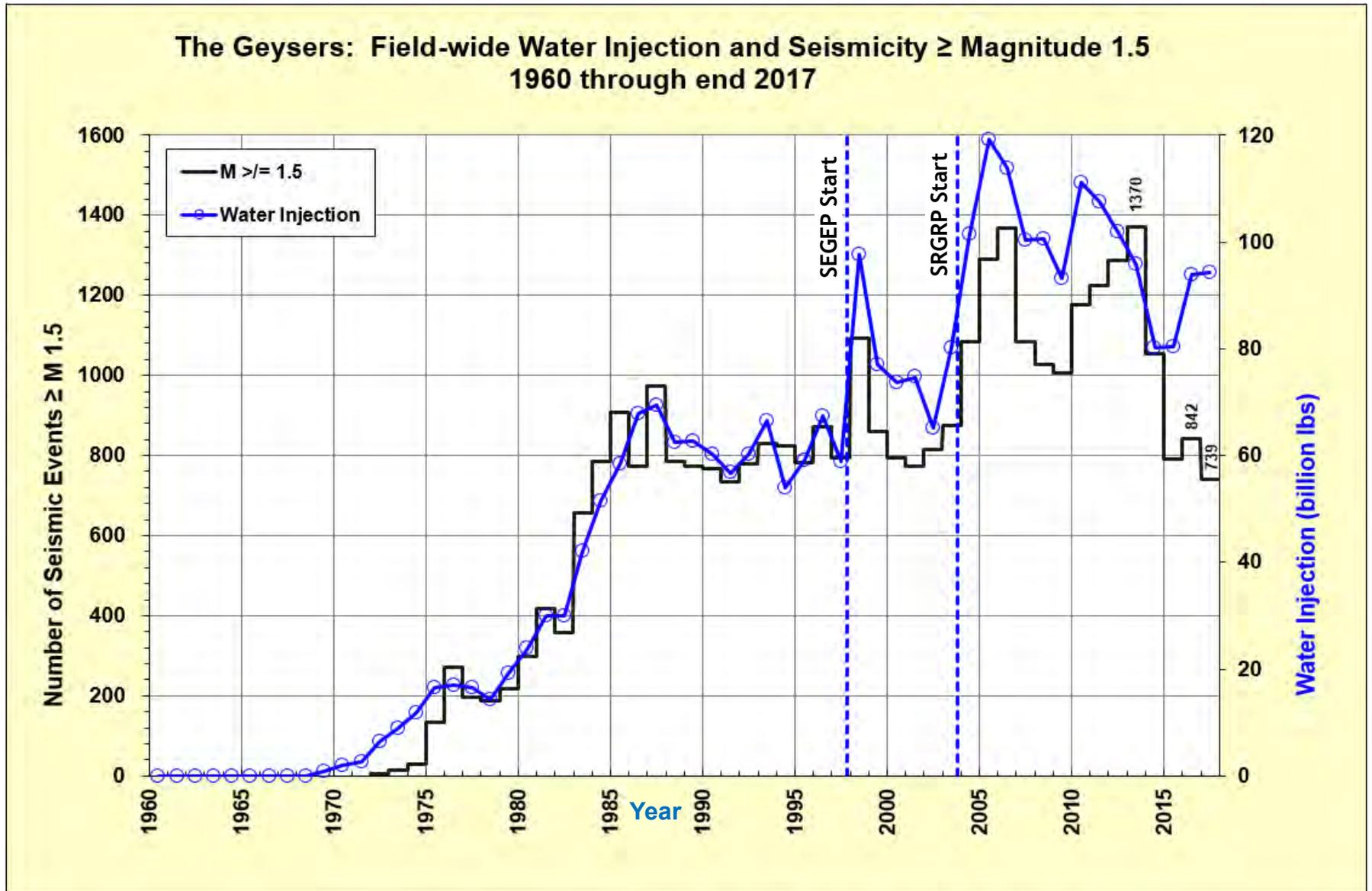
Field-wide Seismicity Analysis  
 Events  $\geq$  Specified Magnitude  
 Sixteen Semi-Annual Periods Since 01 April 2010



# Seismic Monitoring Advisory Committee Meeting

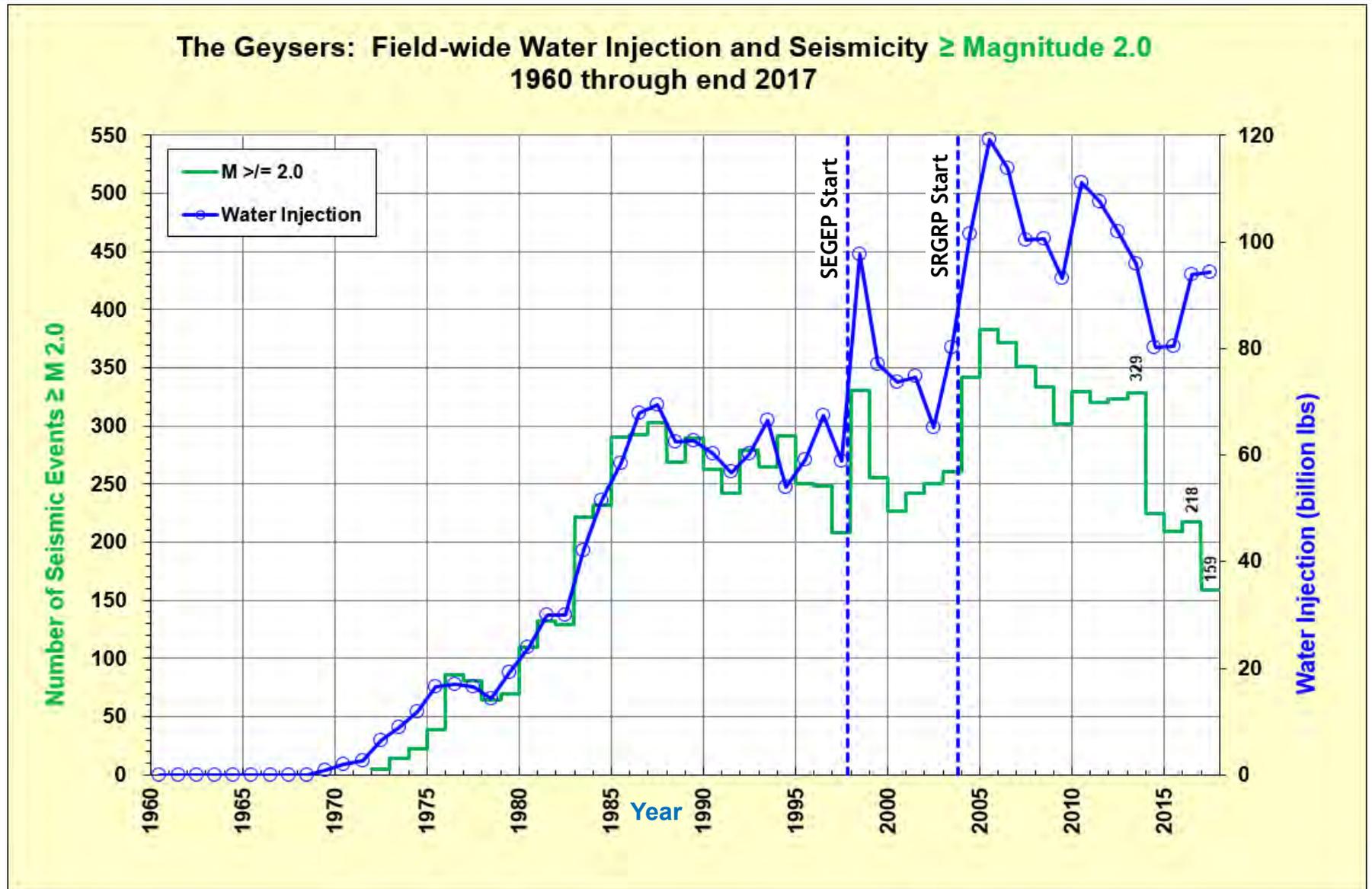
## Yearly Field-wide Steam Production, Water Injection and Seismicity





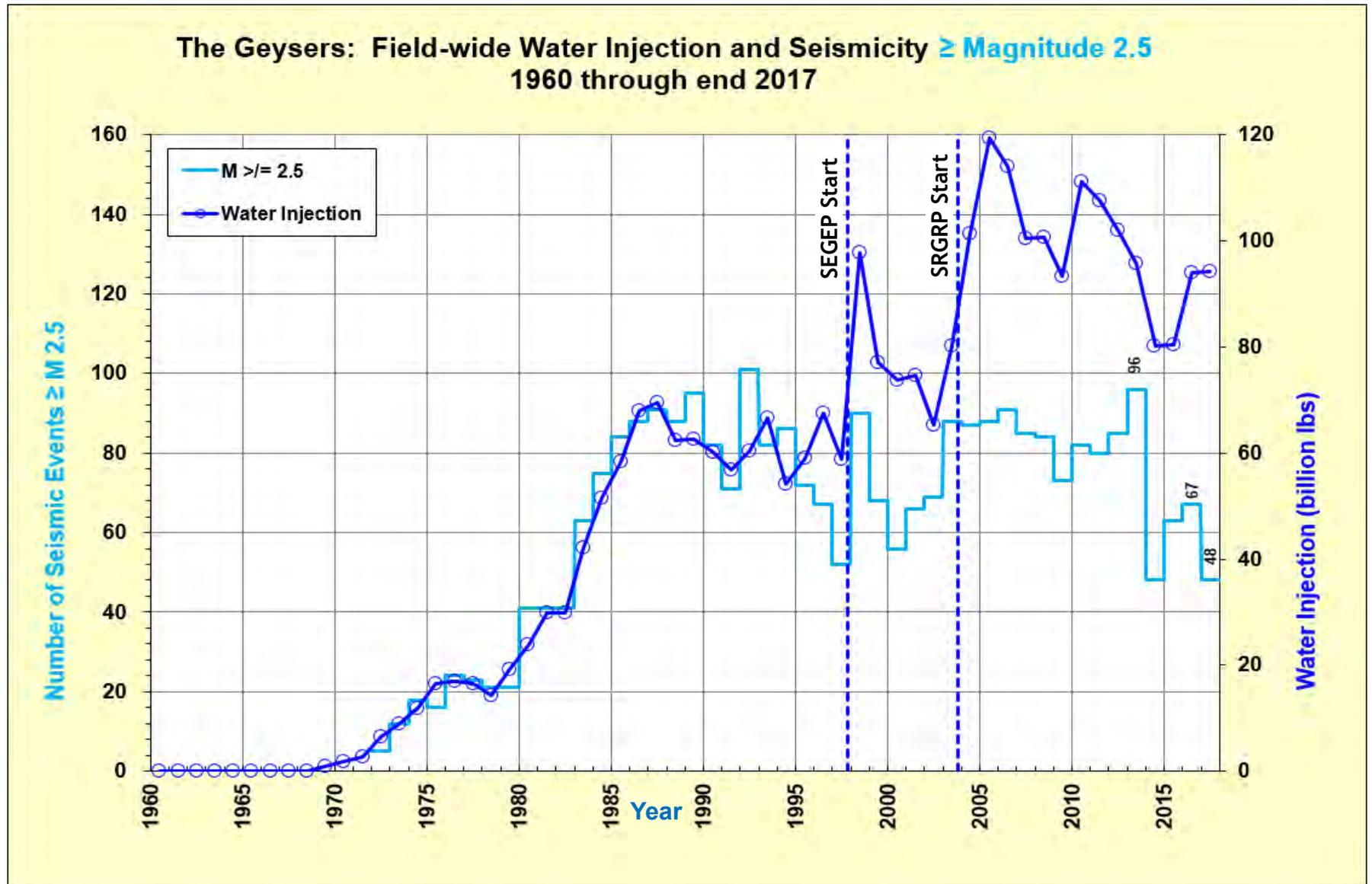
# Seismic Monitoring Advisory Committee Meeting

## Yearly Field-wide Water Injection and Seismicity $\geq$ Magnitude 2.0



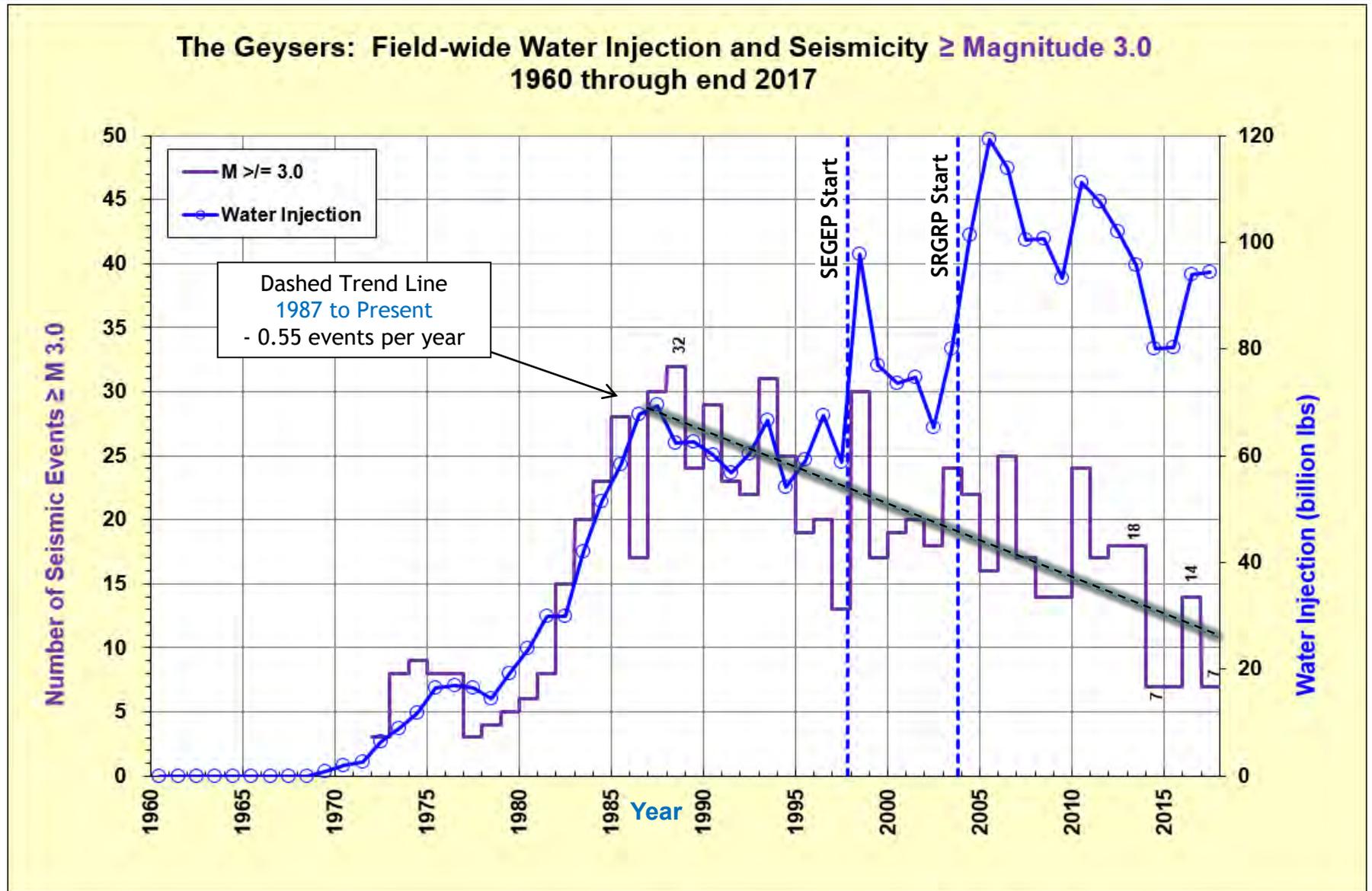
# Seismic Monitoring Advisory Committee Meeting

## Yearly Field-wide Water Injection and Seismicity $\geq$ Magnitude 2.5



# Seismic Monitoring Advisory Committee Meeting

## Yearly Field-wide Water Injection and Seismicity $\geq$ Magnitude 3.0



# Seismic Monitoring Advisory Committee Meeting

## Monthly Field-wide Water Injection By Source vs. Magnitude $\geq 4.0$ Seismicity

Average Number of Magnitude  $\geq 4.0$  Events Per Year Significantly Less Than 2003-2006 Peak

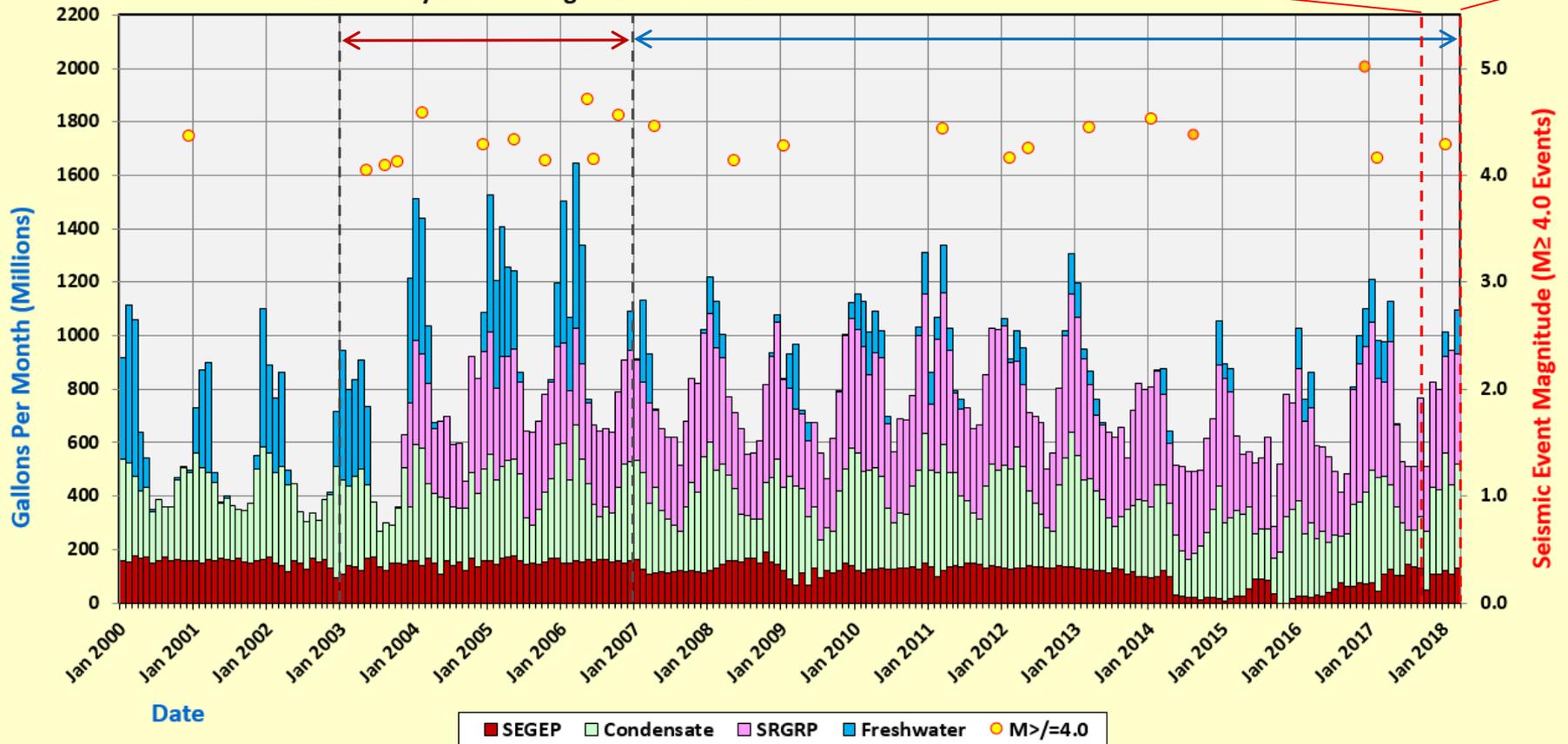
Water Supply for Reporting Period (Six Months)

Water Injection Sources (Gallons)				
Month	SEGEP	SRGRP	Condensate	Fresh Water
October	49,843,000	241,550,000	218,251,010	0
November	108,488,000	394,690,000	324,215,571	0
December	107,527,000	375,250,000	314,305,742	0
January	122,434,000	364,560,000	436,268,490	91,264,006
February	108,737,000	502,040,000	333,067,652	0
March	128,632,000	414,740,000	389,579,727	162,528,067

Time Period Magnitude  $\geq 4.0$  Seismic Events

January 2003 through December 2006	2.50 per year
January 2007 through March 2018	1.06 per year

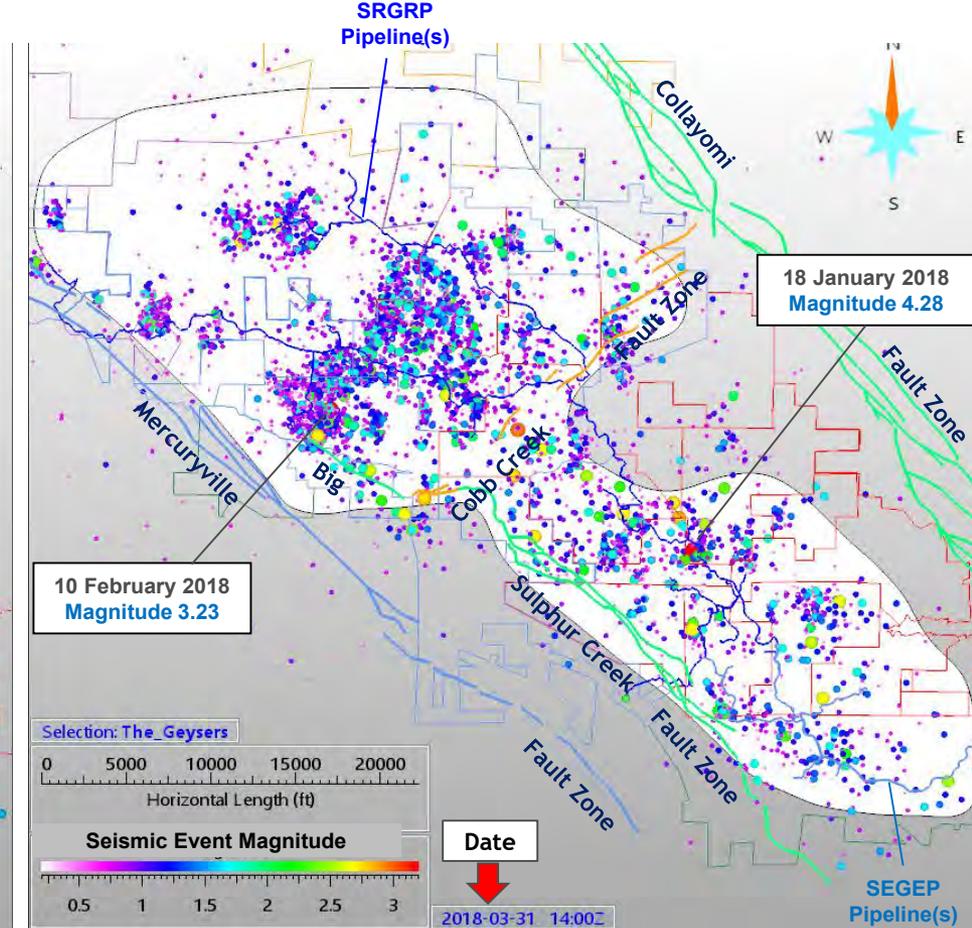
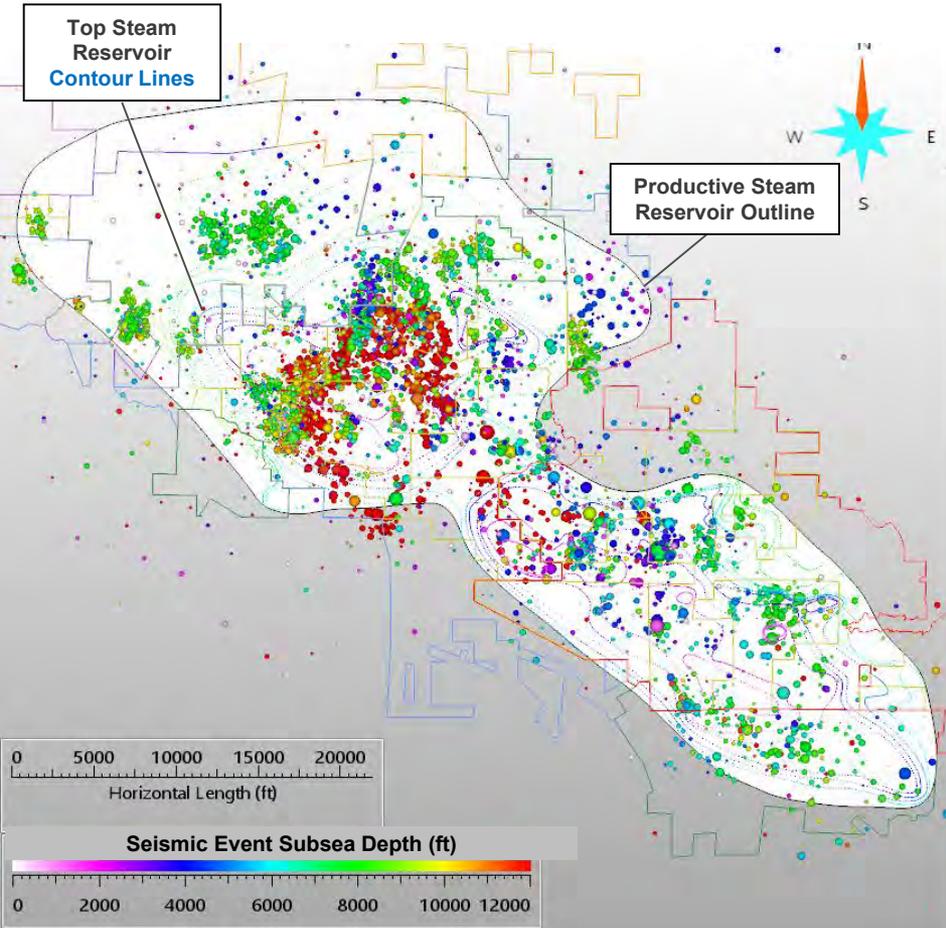
The Geysers  
Calpine Fieldwide Water Injection Sources  
Magnitude  $\geq 4.0$  Seismicity  
01 January 2000 through 31 March 2018



# Seismic Monitoring Advisory Committee Meeting

## Fieldwide Induced Seismicity Animation

01 October 2017 to 31 March 2018



**U.S. Geological Survey Faults**

< 150 years	Red line
< 15,000 years	Orange line
< 130,000 years	Green line
< 1,600,000 years	Blue line

# Seismic Monitoring Advisory Committee Meeting

## Calpine Community Hotline

The communities continue to focus on efforts to recover from the Valley Fire, resulting in only **two calls** to the Calpine Community Hotline during the current reporting period of **01 October 2017 to 31 March 2018**. The seismic event responsible for both calls:

### Magnitude 4.28 Seismic Event

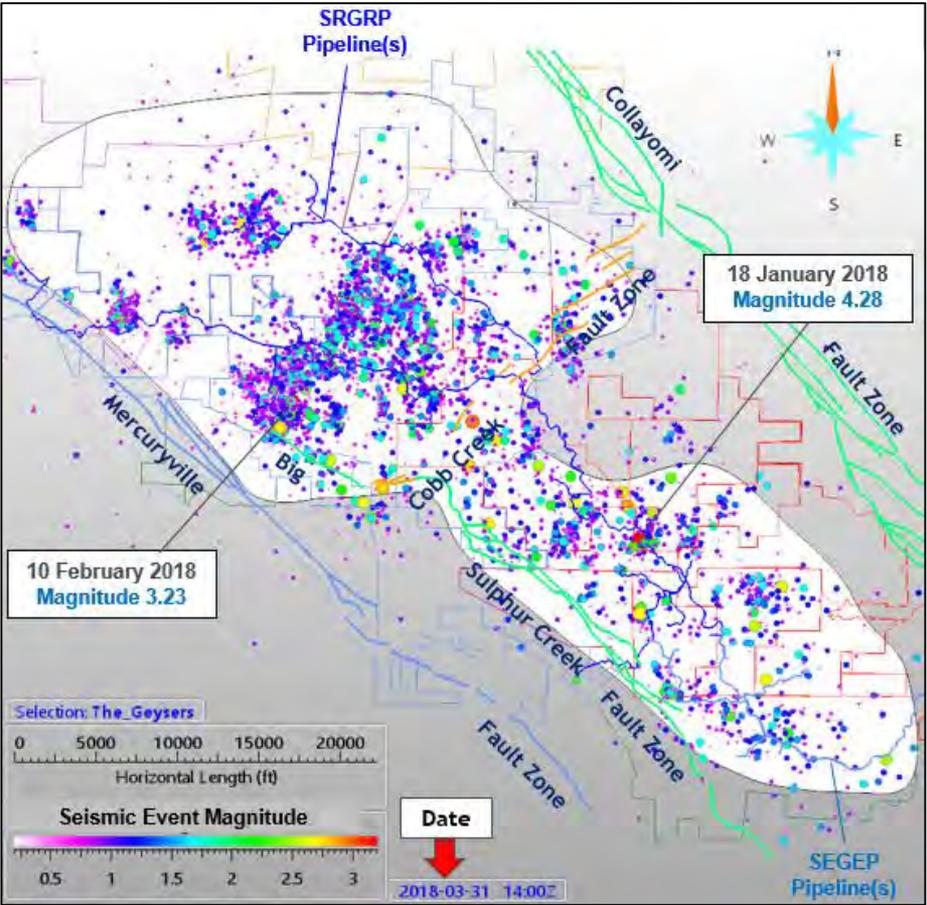
Date and Time: 17 January 2018 at 21:55:12 Pacific Time  
18 January 2018 at 05:55:12 UTC  
Latitude: North 38.78500  
Longitude: West 122.74333  
Depth: 5940 Feet (1.81 km) Below Sea Level

### Anderson Springs

Call on 18 January 2018 at 11:24 am  
“One of the stronger events experienced. It definitely got our attention and shook the house for a bit longer than usual.”  
No call back requested.

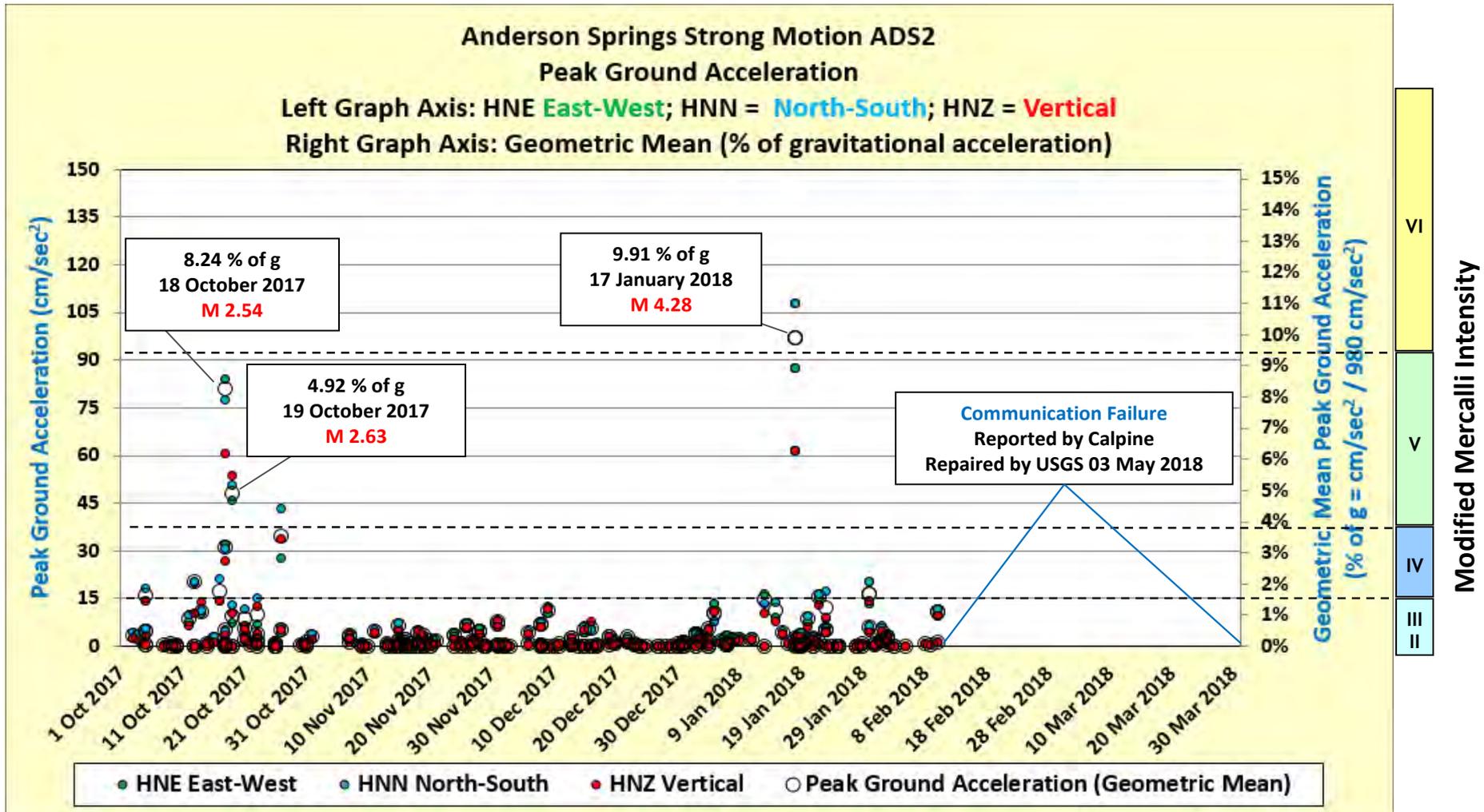
### Cobb

Call on 22 January 2018 at 11:49 am  
“I have some questions about the recent earthquake on Wednesday at about 9:50 pm”  
Call back requested.  
Danielle Mathews Seperas and Craig Hartline provided the caller with scientific information concerning the 4.28 seismic event and Calpine’s community relations program, including the semi-annual Seismic Monitoring Advisory Committee meetings.



# Seismic Monitoring Advisory Committee Meeting

## 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

## Center for Engineering Strong Motion Data

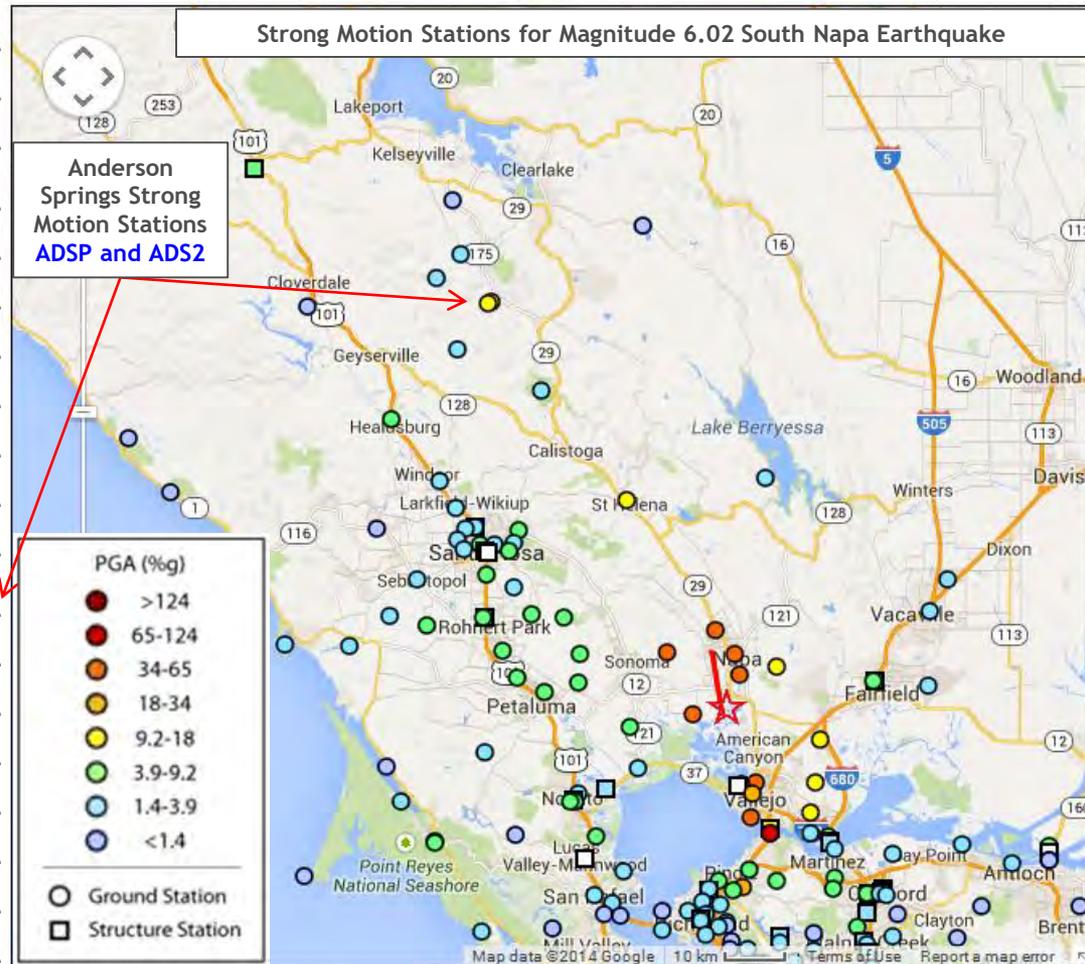
### Magnitude 6.02 South Napa Earthquake

16 October 2014

USGS submitted strong motion records to the Center for Engineering Strong Motion Data  
 ADSP and ADS2 not consistent with regional patterns for peak ground acceleration

event link: [http://strongmotioncenter.org/cgi-bin/CESMD/iqr\\_dist\\_DM2.pl?iqrID=SouthNapa\\_24Aug2014\\_72282711&SFlag=0&Flag=2](http://strongmotioncenter.org/cgi-bin/CESMD/iqr_dist_DM2.pl?iqrID=SouthNapa_24Aug2014_72282711&SFlag=0&Flag=2)

Station	Code ID	Network	Distance (km)		Peak Ground Acceleration ↓ relative to g
			Epic.	Fault	
<a href="#">Crockett - Carquinez Br Geotech Array #1</a>	68206	CGS	19.6	--	0.995
<a href="#">Main St, Napa, CA</a>	N016	NCSN	9.1	4.4	0.611
<a href="#">Vallejo - Broadway &amp; Sereno</a>	68294	CGS	11.7	12.1	0.469
<a href="#">Crockett - Carquinez Br Geotech Array #2</a>	68259	CGS	19.5	--	0.436
<a href="#">Napa: Fire Station No. 3</a>	1765	USGS	12.3	3.3	0.427
<a href="#">Huichica Creek</a>	NHC	NCSN	3.5	4.4	0.403
<a href="#">Napa - Napa College</a>	68150	CGS	7.1	4.5	0.375
<a href="#">Mare Island</a>	NMI	NCSN	16.7	16.8	0.369
<a href="#">Lovall Valley Loop Rd</a>	N019B	NCSN	12.0	6.4	0.342
<a href="#">Vallejo: Fire Station</a>	1759	USGS	13.4	13.6	0.329
<a href="#">Pinole - Adobe &amp; Pinole Valley Rd</a>	58368	CGS	26.3	26.9	0.203
<a href="#">Vallejo - Hwy 37/Napa River E Geo. Array</a>	68310	CGS	11.0	--	0.198
<a href="#">Anderson Springs</a>	ADSP	USGS	70.4	--	0.174
<a href="#">CA: Anderson Springs; Town Pool</a>	ADS2	USGS	70.2	--	0.159
<a href="#">Vallejo - Carquinez/180 East Bridge</a>	68184	CGS	18.9	19.4	0.149
<a href="#">McCall Drive, Benicia, CA</a>	C032	NCSN	20.3	20.6	0.140
<a href="#">Green Valley Road</a>	NGVB	NCSN	11.5	9.7	0.110
<a href="#">St. Helena: Fire Station No. 17</a>	1764	USGS	34.7	25.0	0.104
<a href="#">Lake Herman</a>	NLH	NCSN	18.0	18.1	0.094



# Seismic Monitoring Advisory Committee Meeting

## Center for Engineering Strong Motion Data

### Engels Strong Motion ESM

The Engels Strong Motion station data is transferred by radio telemetry to the LBNL seismic monitoring network and accessible at the [Center for Engineering Strong Motion Data\\*](https://www.strongmotioncenter.org/), a cooperative effort of the [United States Geological Survey](https://www.usgs.gov/), [California Geological Survey](https://www.cgs.gov/) and the [Advanced National Seismic System](https://www.anss.org/).

**CESMD** Strong-Motion Data Set

Home Archives Search Earthquake/Station Maps About

Internet Data Report



**The Geysers Earthquake of 17 Jan 2018**  
 4.2MW, 21:55:11 PST, 38.7850N 122.7433W Depth 1.8 km



Center for Engineering Strong Motion Data

CESMD - A Cooperative Effort



Interactive Map



ShakeMap

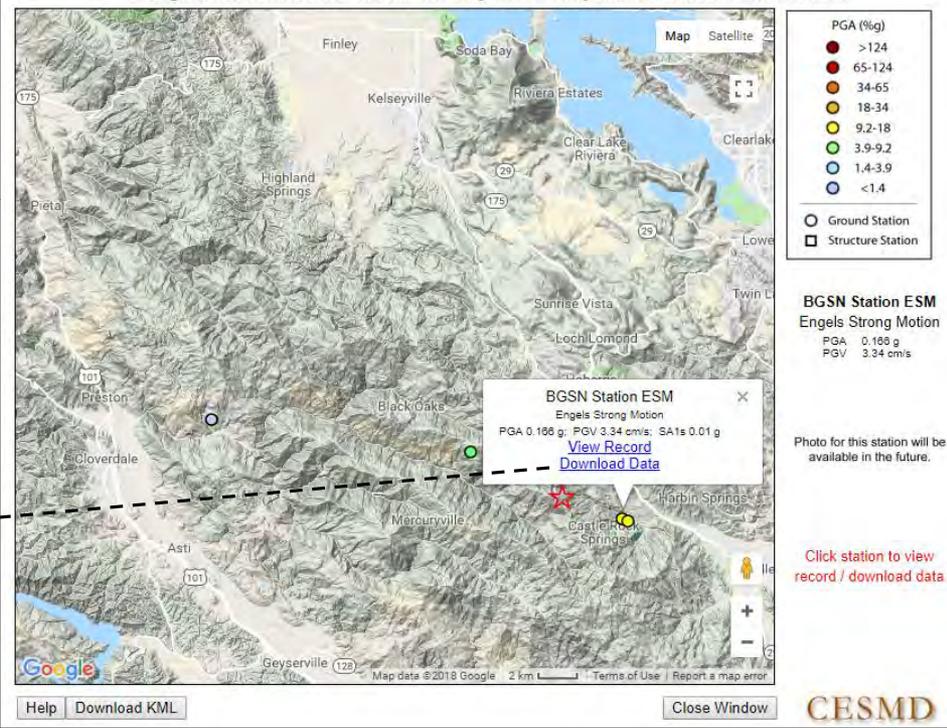


Download Table

Station	Code /ID	Network	Distance (km)		Horiz. Apk (g)	
			Epic.	Fault	Ground	Struct.
Engels Strong Motion	ESM	BGSN	3.6	--	0.166	--
CA: Anderson Springs; Town Pool	ADS2	NSMP	4.0	--	0.112	--
Geysers	GDXB	NCSN	5.2	--	0.079	--
Hale Ranch	DRH	BGSN	18.7	--	0.006	--

Last Update

Strong Motion Stations for 4.2MW The Geysers Earthquake of 17 Jan 2018, 2155 PST



**Channel 90 Degree (East-West)**  
 Peak acceleration = -133.428 cm/sec/sec  
 Peak velocity = 2.285 cm/sec  
 Peak displacement = -.062 cm

**Channel 360 Degree (North-South)**  
 Peak acceleration = -157.753 cm/sec/sec  
 Peak velocity = 3.339 cm/sec  
 Peak displacement = -.181 cm

\* <https://www.strongmotioncenter.org/>

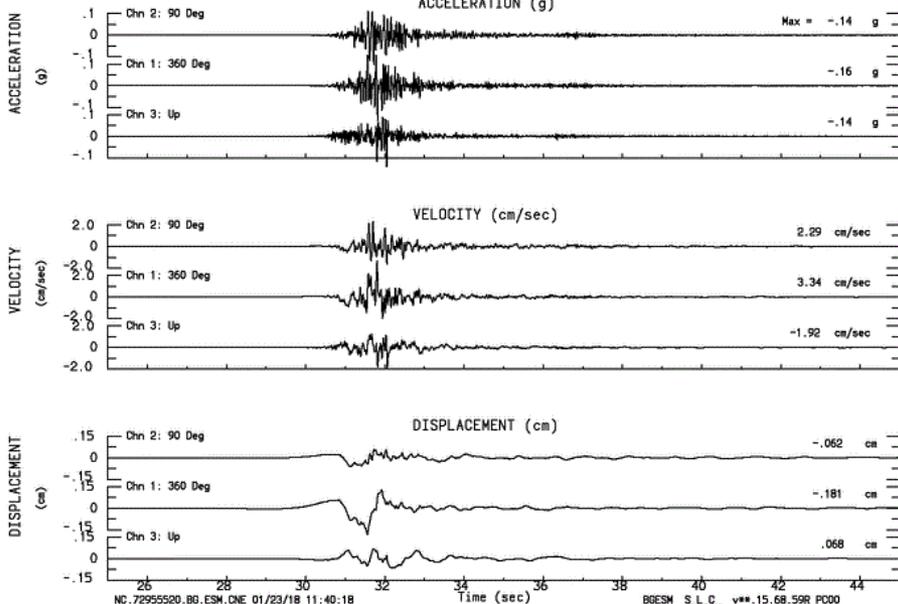
# Seismic Monitoring Advisory Committee Meeting

## Center for Engineering Strong Motion Data

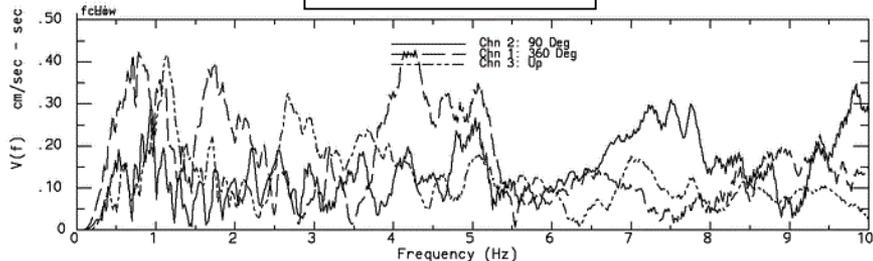
### Engels Strong Motion ESM

#### Acceleration, Velocity and Surface Displacement

Engels Strong Motion BGSN Sta ESM  
 Rcrd of Wed Jan 17, 2018 21:54:42.8 PST  
 Frequency Band Processed: 3.3 secs to 40.0 Hz  
 CISM/CSMP Preliminary Strong Motion Processing - Subject to Revision



#### Spectral Analysis

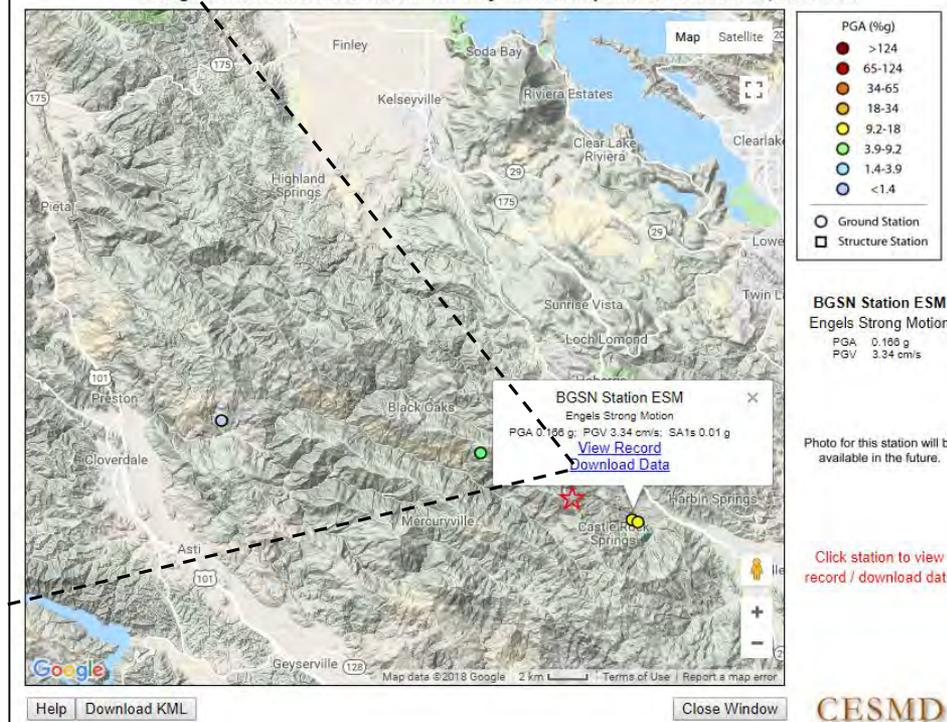


Center for Engineering Strong Motion Data

CESMD - A Cooperative Effort



#### Strong Motion Stations for 4.2MW The Geysers Earthquake of 17 Jan 2018, 2155 PST



\* <https://www.strongmotioncenter.org/>

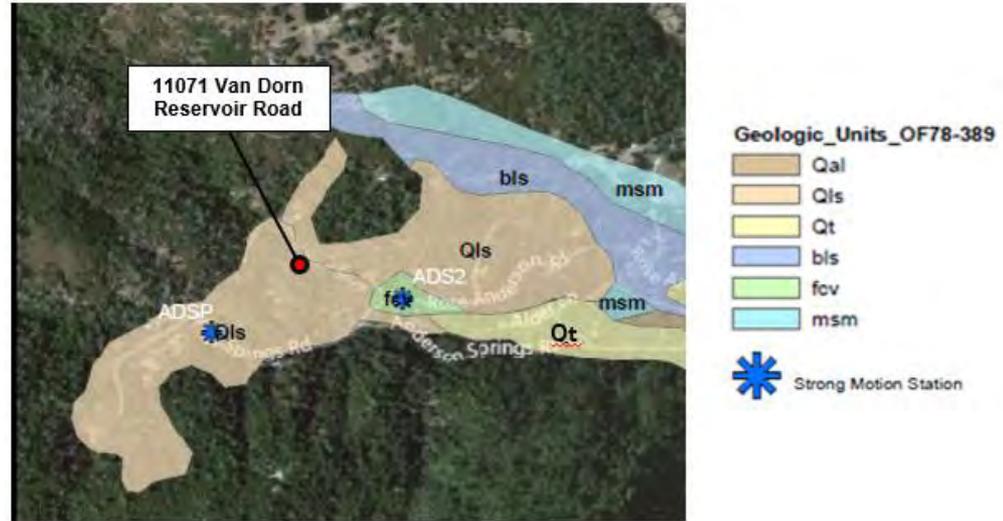
# Seismic Monitoring Advisory Committee Meeting

## Anderson Springs Strong Motion Station

### Engels Strong Motion ESM vs Fire-Damaged ADSP Strong Motion

#### Site Selection Criteria to Replace ADSP

- 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



#### ADSP and Engels Strong Motion (ESM) Stations

- 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)
- ESM measurements very consistent with relatively high peak ground acceleration values at ADSP
- consistently higher measurements than ADS2

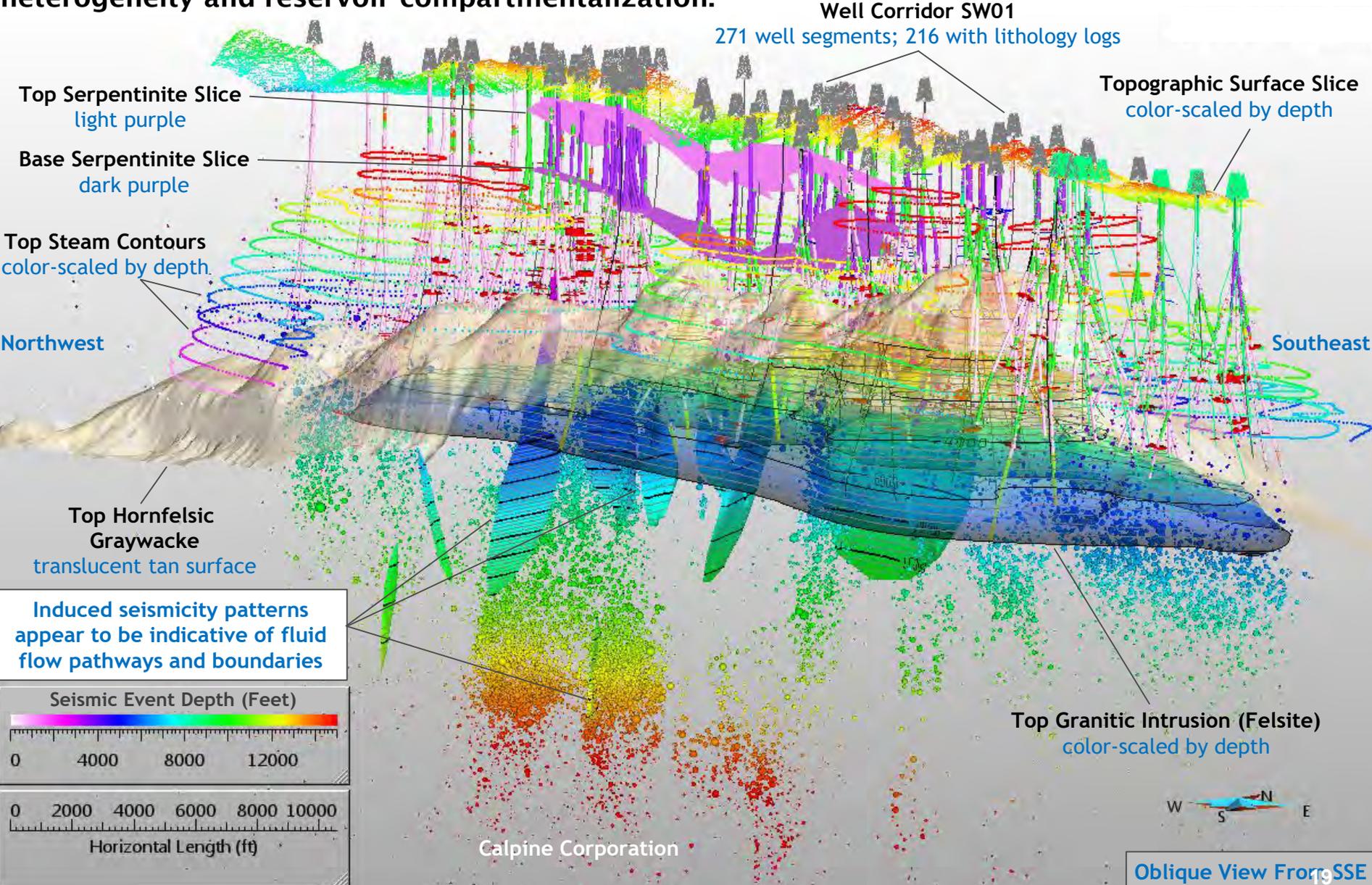
M 4.2 2018-01-17 21:55:11 Pacific Time					
Engels Strong Motion (ESM)					
HNE cm/sec <sup>2</sup>	HNN cm/sec <sup>2</sup>	HNZ cm/sec <sup>2</sup>	Geometric Mean	g	% of g
133.42800	157.75300	76.49680	145.08	0.15	14.8

ADSP 9.9% → ESM 14.8%

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

**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

## Calpine Geysers Water Injection Goals

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### Improve Injection Distribution

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

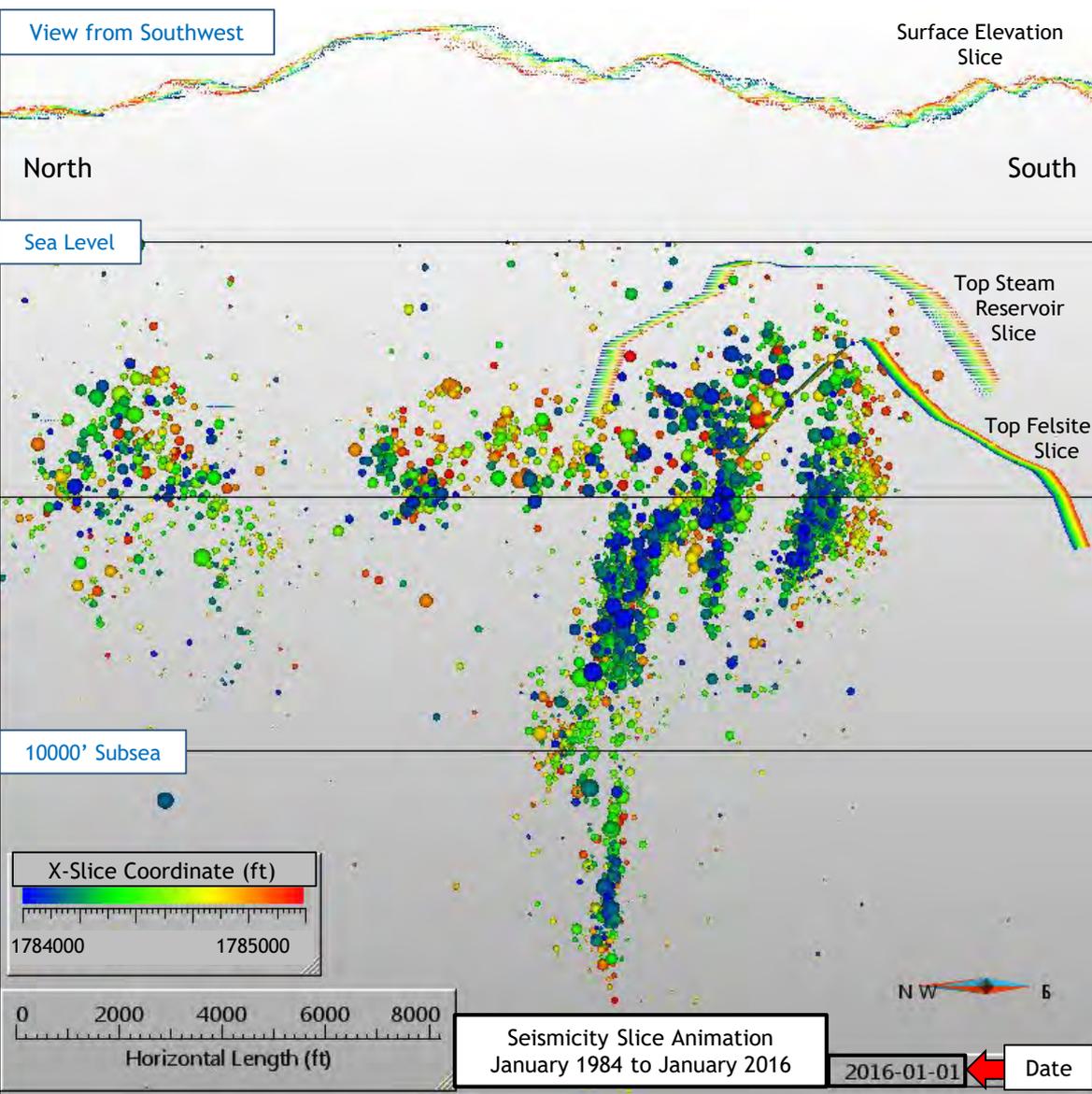
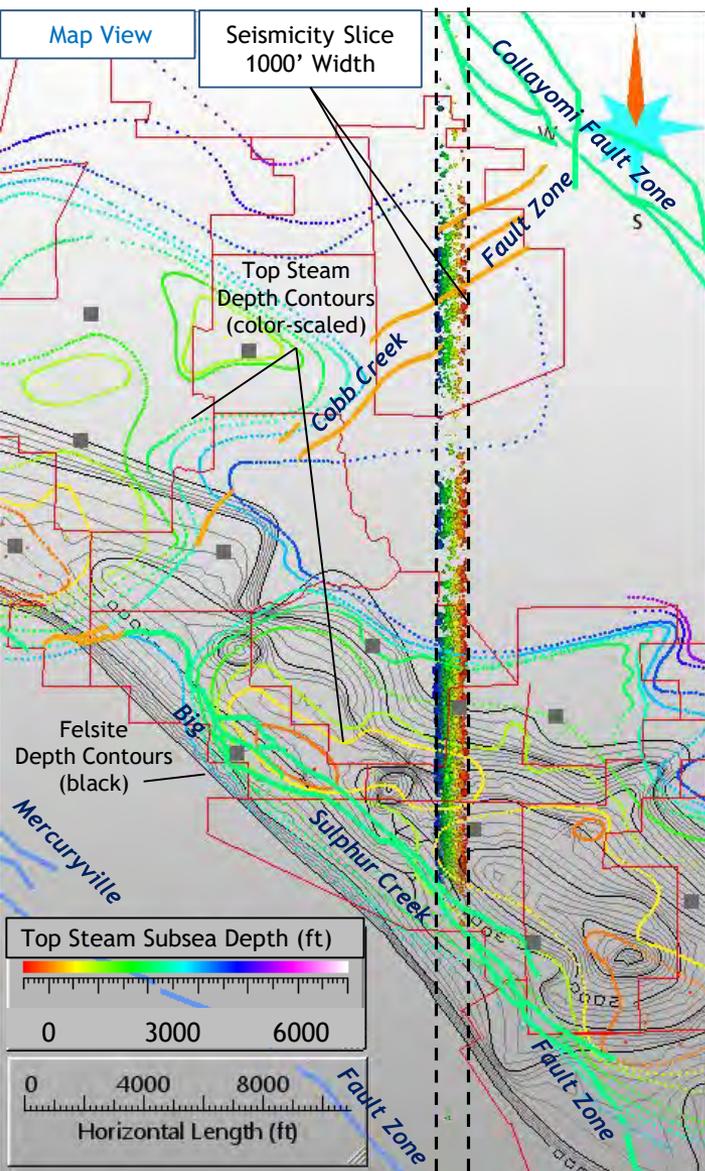
### Minimize Injection Rate Variations

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



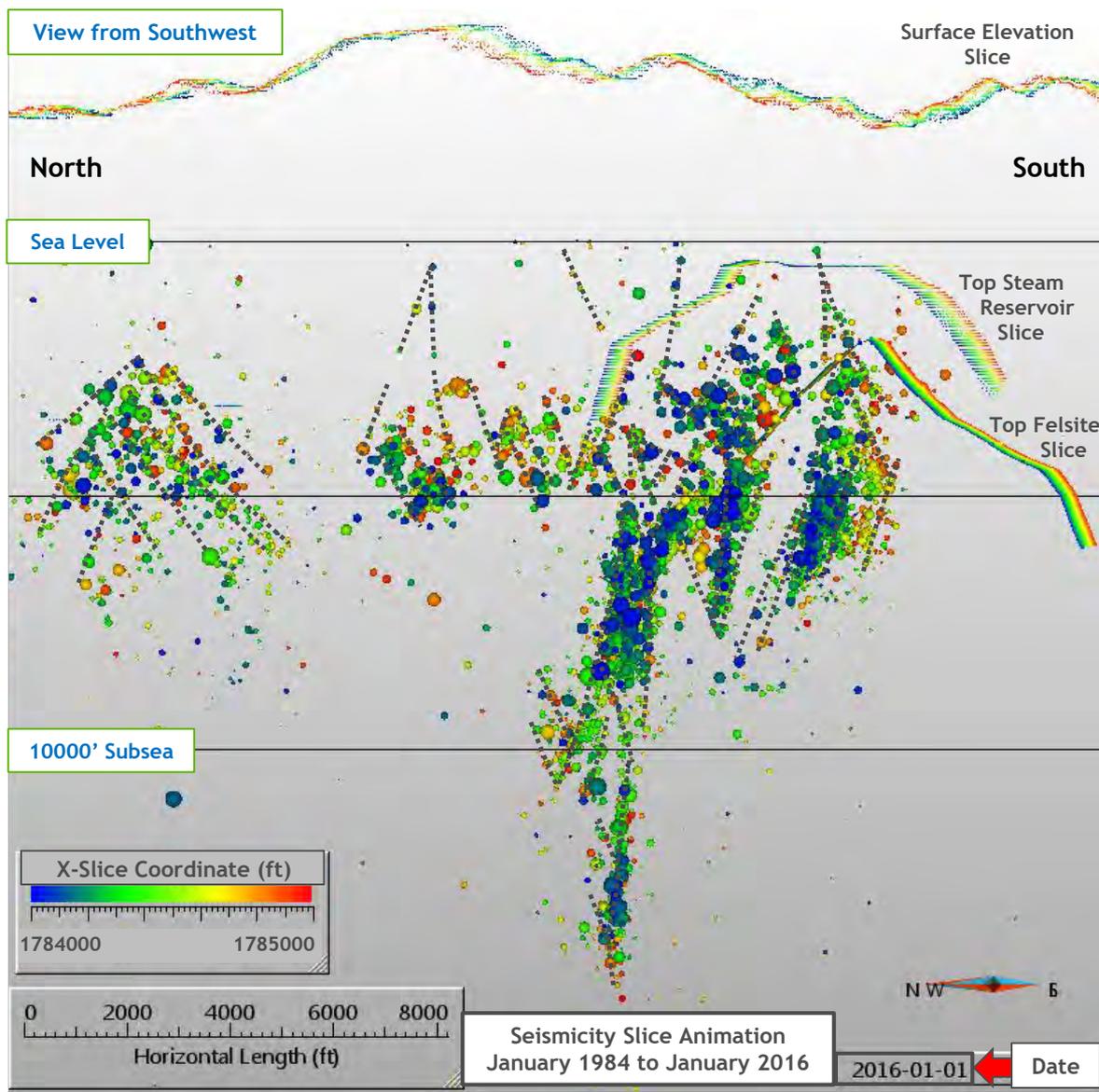
# Seismic Monitoring Advisory Committee Meeting

## Seismicity Slice Analysis and Fracture Zone Interpretation



# Seismic Monitoring Advisory Committee Meeting

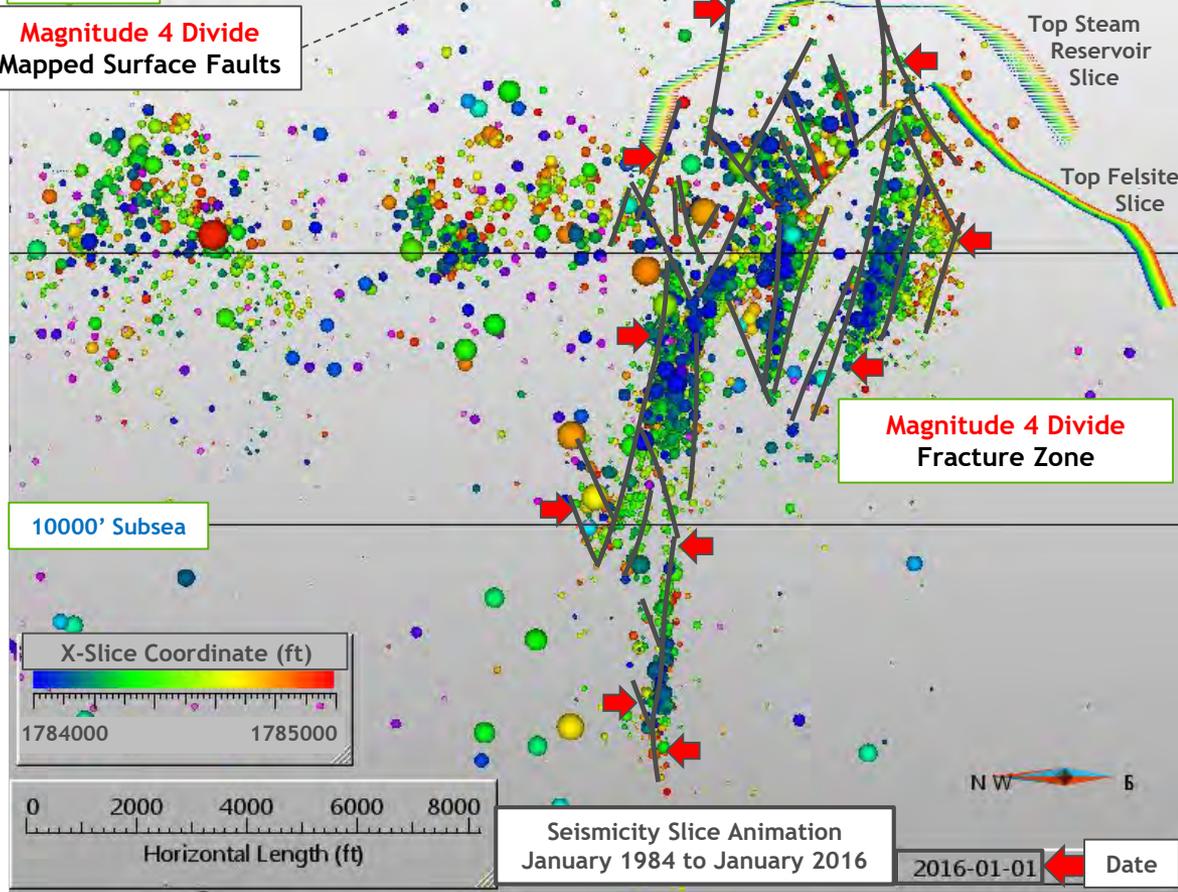
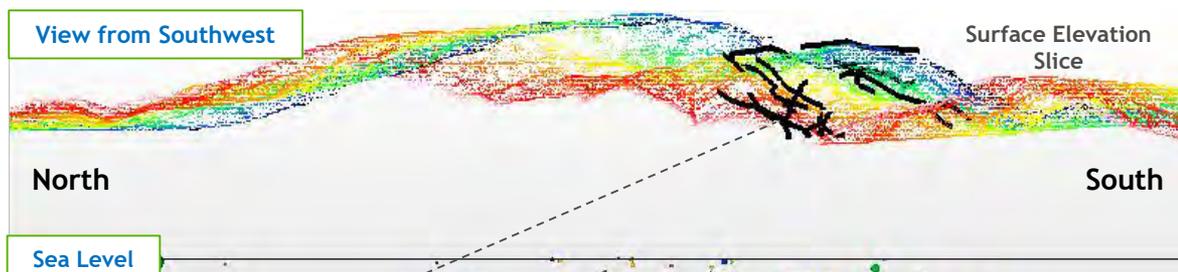
## Seismicity Slice Analysis and Fracture Zone Interpretation



# Seismic Monitoring Advisory Committee Meeting

## Seismicity Slice Analysis and Fracture Zone Interpretation

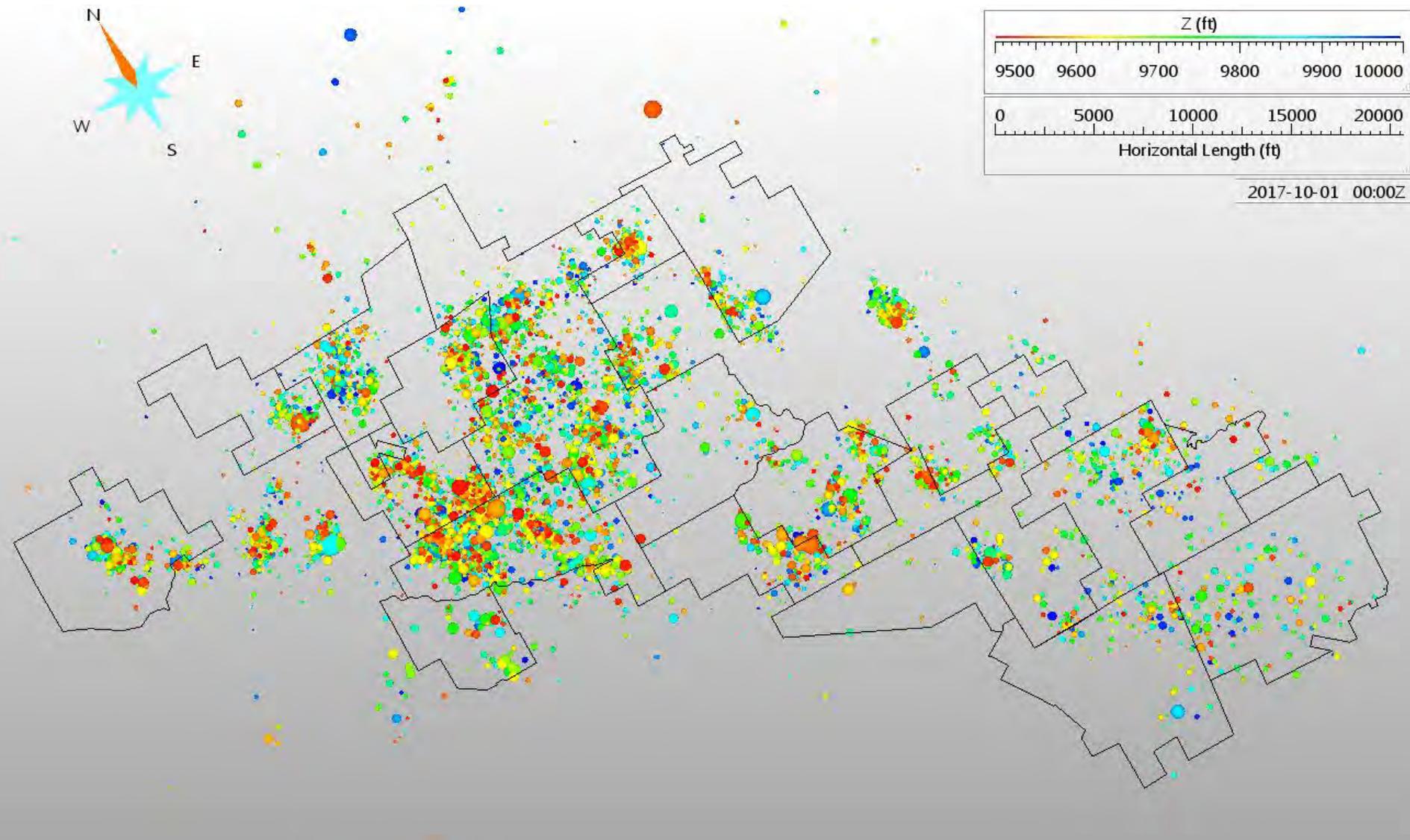
### "Magnitude 4 Divide"



# Seismic Monitoring Advisory Committee Meeting

## Fault/Fracture Analysis and Interpretation

### Depth Slice 9500 to 10000 Feet Subsea



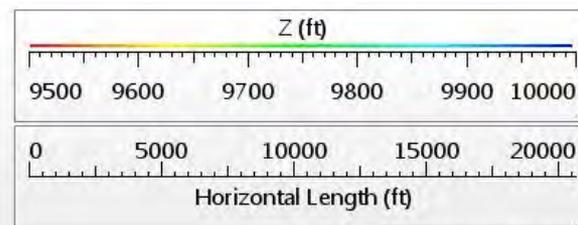
# Seismic Monitoring Advisory Committee Meeting

## Fault/Fracture Analysis and Interpretation

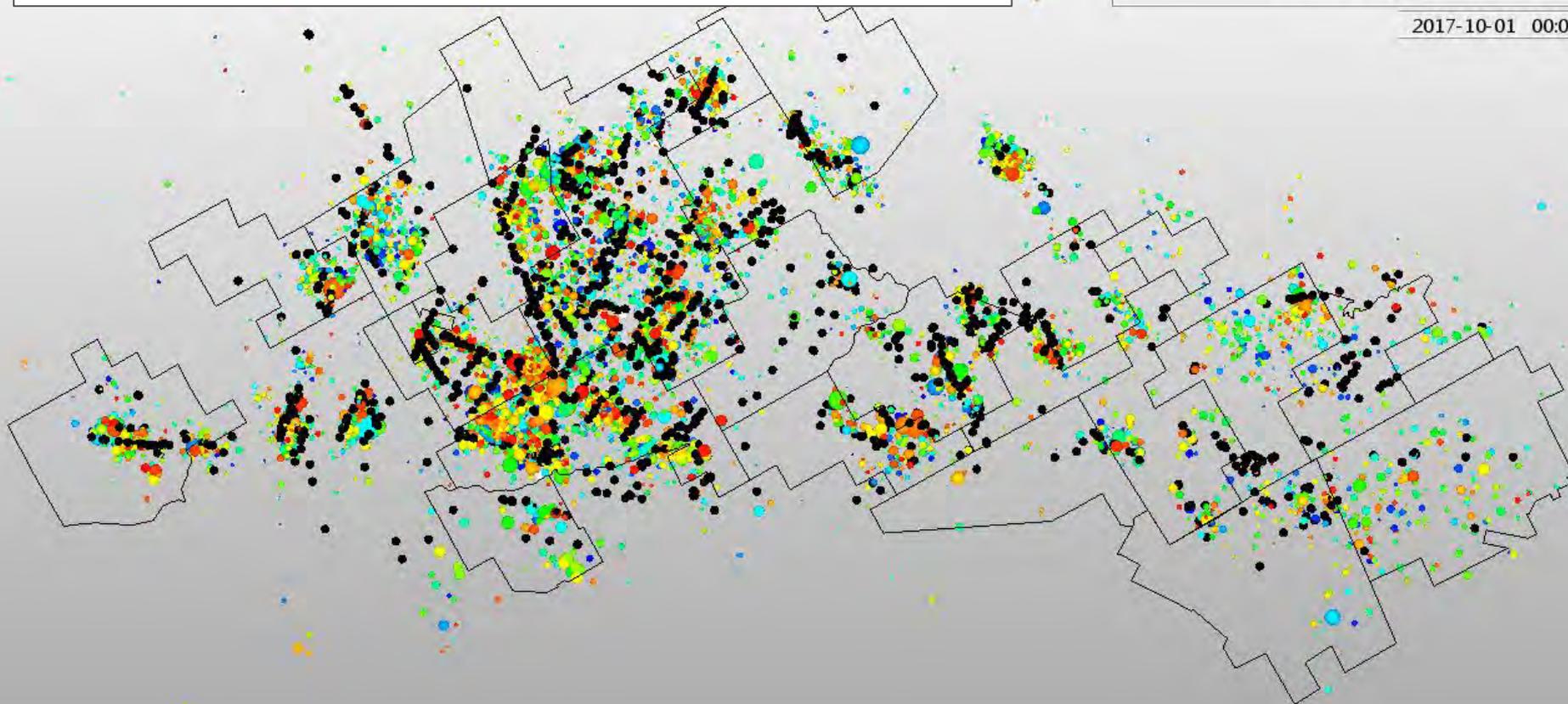
### Depth Slice 9500 to 10000 Feet Subsea



Seismicity hypocenters alignments present on several successive seismicity slices are “interpreted” as flow path surfaces (fractures or fracture networks) and barriers\*. Restricting the seismicity slice thickness to ~500’ allows detailed analysis\*.



2017-10-01 00:00Z

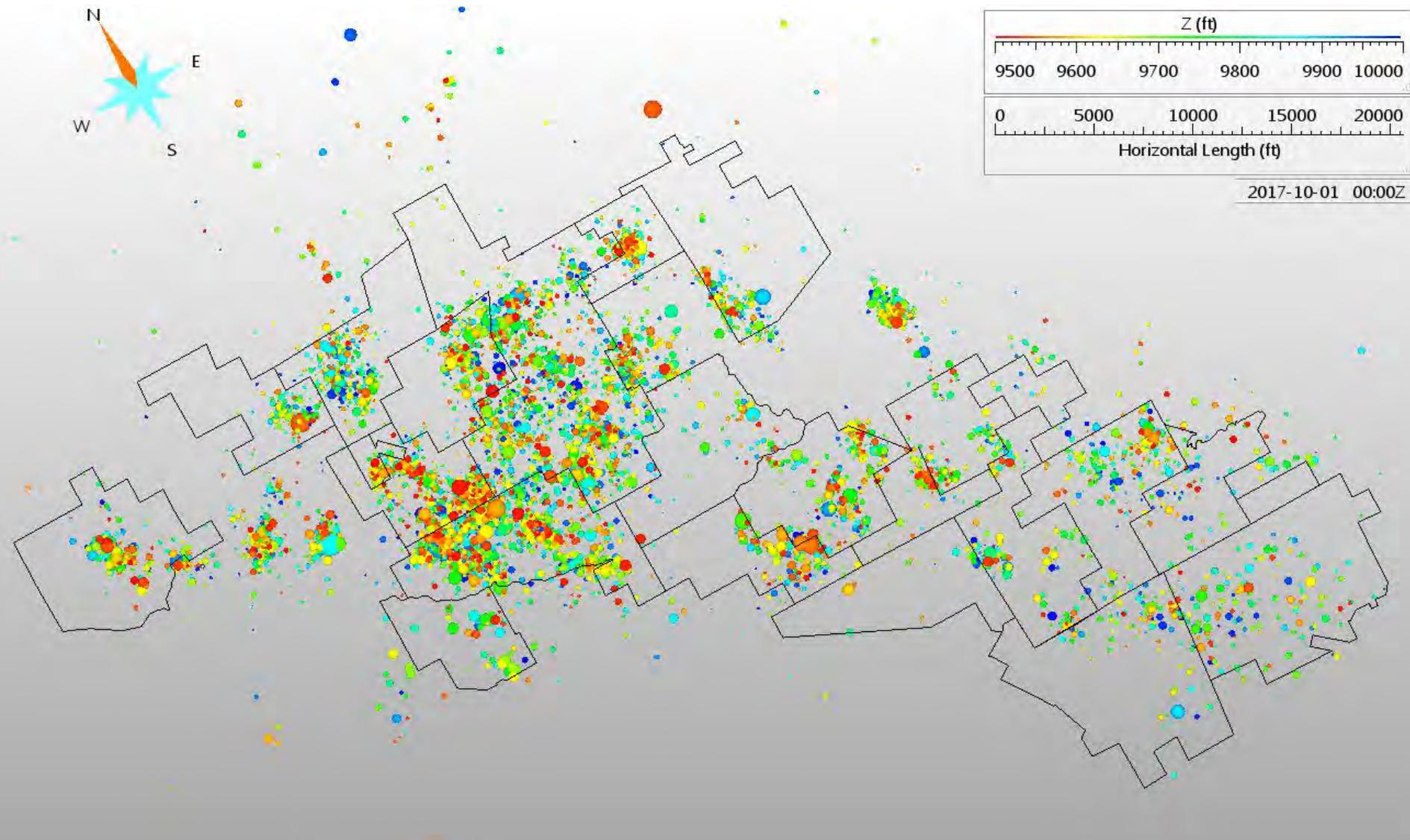


\* Barrier: A physical feature that tends to limit or prevent the free movement and mixing of populations or individuals.

# Seismic Monitoring Advisory Committee Meeting

## Fault/Fracture Analysis and Interpretation

### Depth Slice 9500 to 10000 Feet Subsea



# Seismic Monitoring Advisory Committee Meeting

## Fault/Fracture Analysis and Interpretation

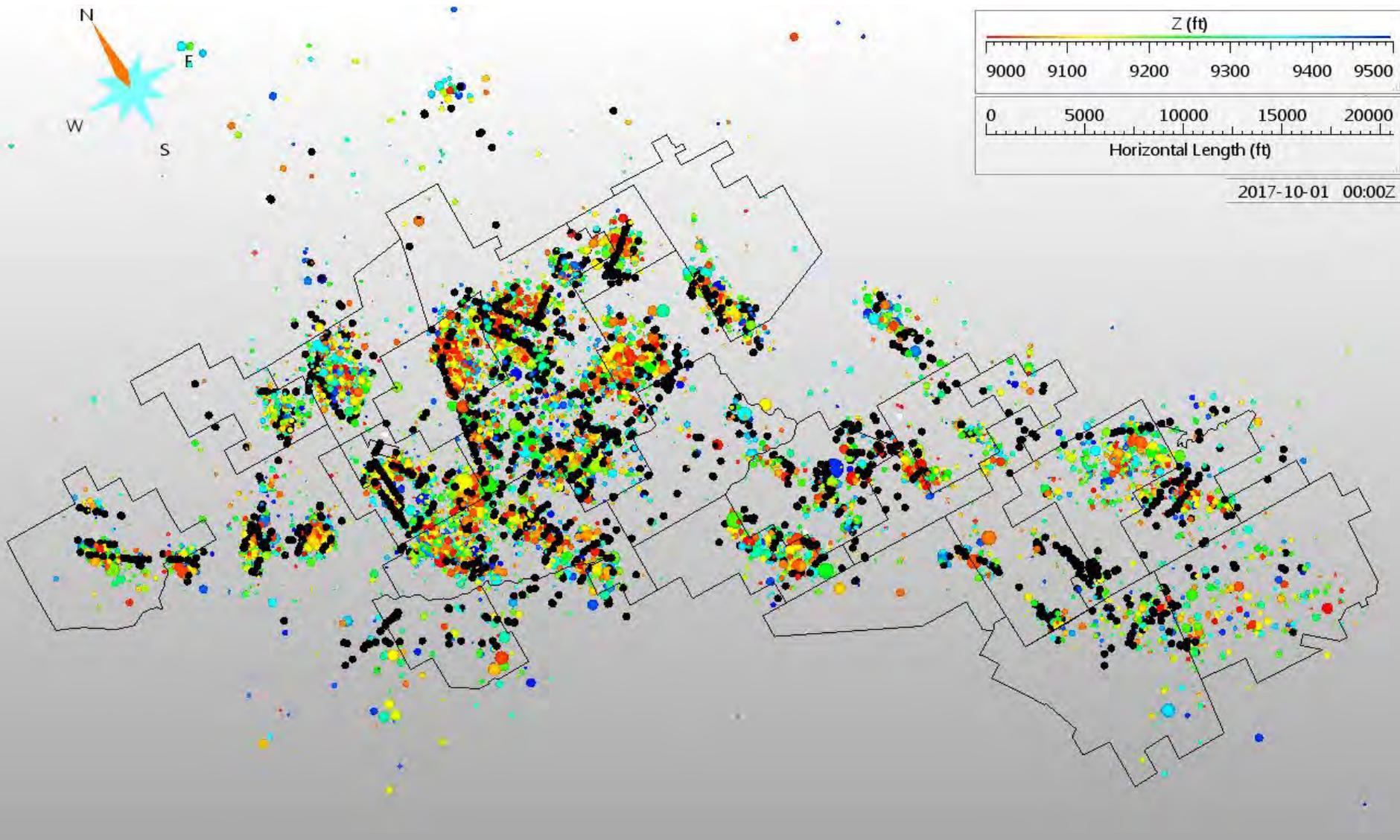
### Depth Slice 9000 to 9500 Feet Subsea



# Seismic Monitoring Advisory Committee Meeting

## Fault/Fracture Analysis and Interpretation

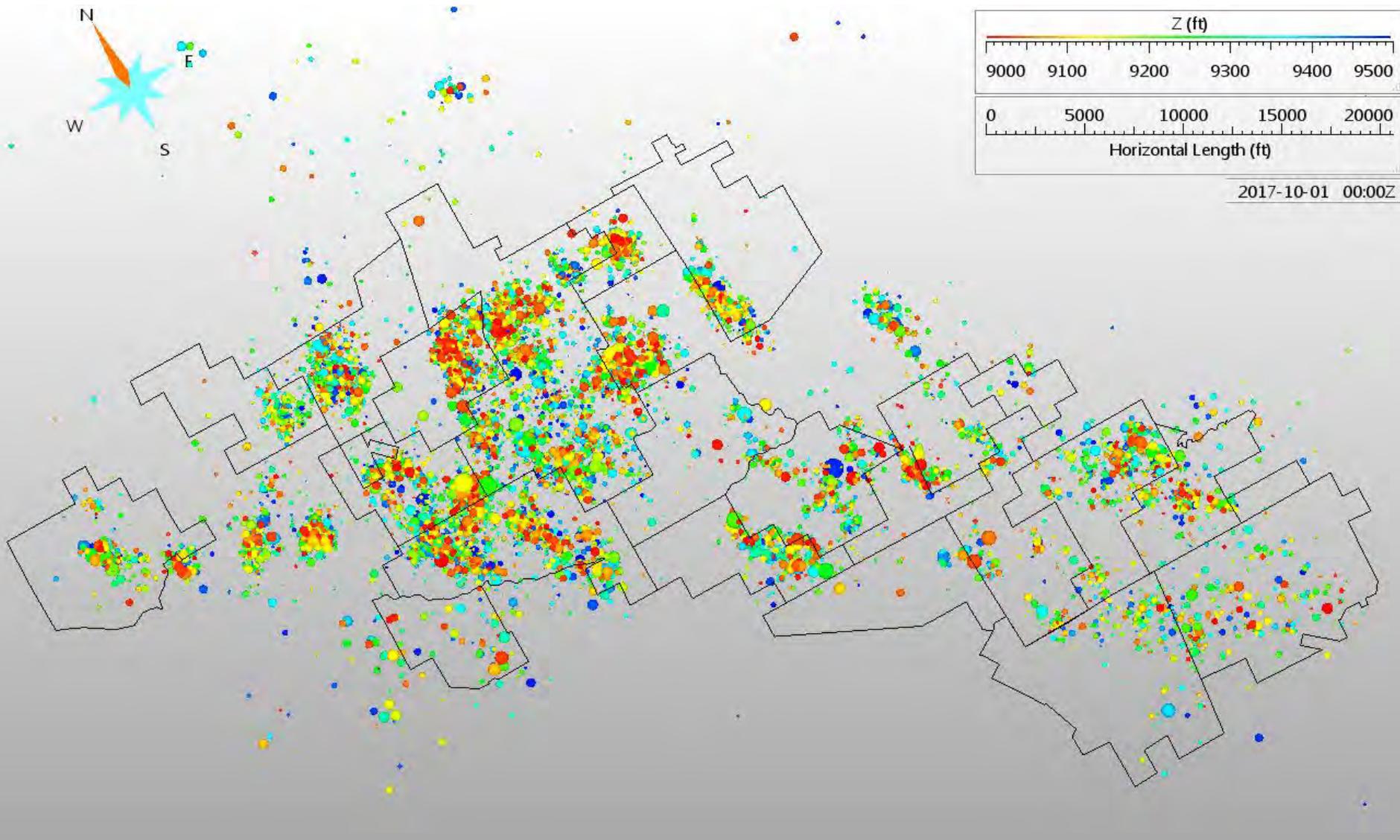
### Depth Slice 9000 to 9500 Feet Subsea



# Seismic Monitoring Advisory Committee Meeting

## Fault/Fracture Analysis and Interpretation

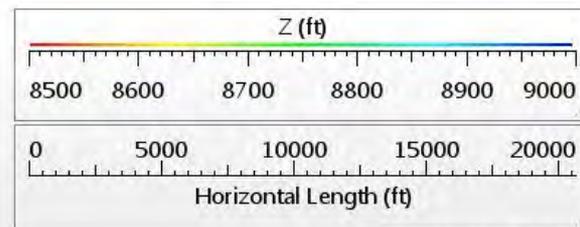
### Depth Slice 9000 to 9500 Feet Subsea



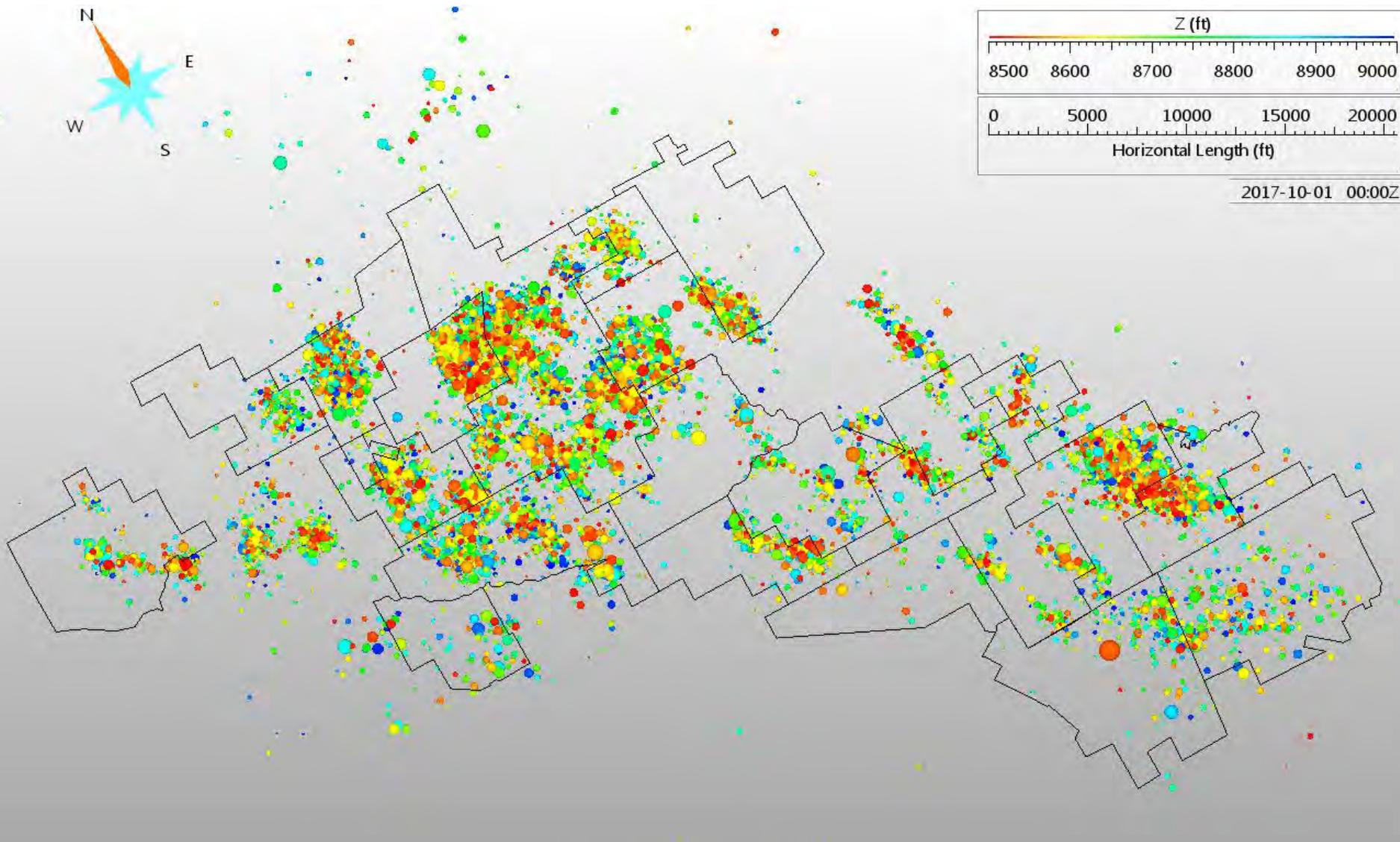
# Seismic Monitoring Advisory Committee Meeting

## Fault/Fracture Analysis and Interpretation

### Depth Slice 8500 to 9000 Feet Subsea



2017-10-01 00:00Z



# Seismic Monitoring Advisory Committee Meeting

## Fault/Fracture Analysis and Interpretation

### Depth Slice 8500 to 9000 Feet Subsea

