
# Seismic Monitoring Advisory Committee Meeting

## 01 April 2021 to 30 September 2021 Reporting Period

Calpine Geothermal Visitor Center

08 November 2021

Craig Hartline
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# Seismic Monitoring Advisory Committee Meeting
## Presentation Agenda

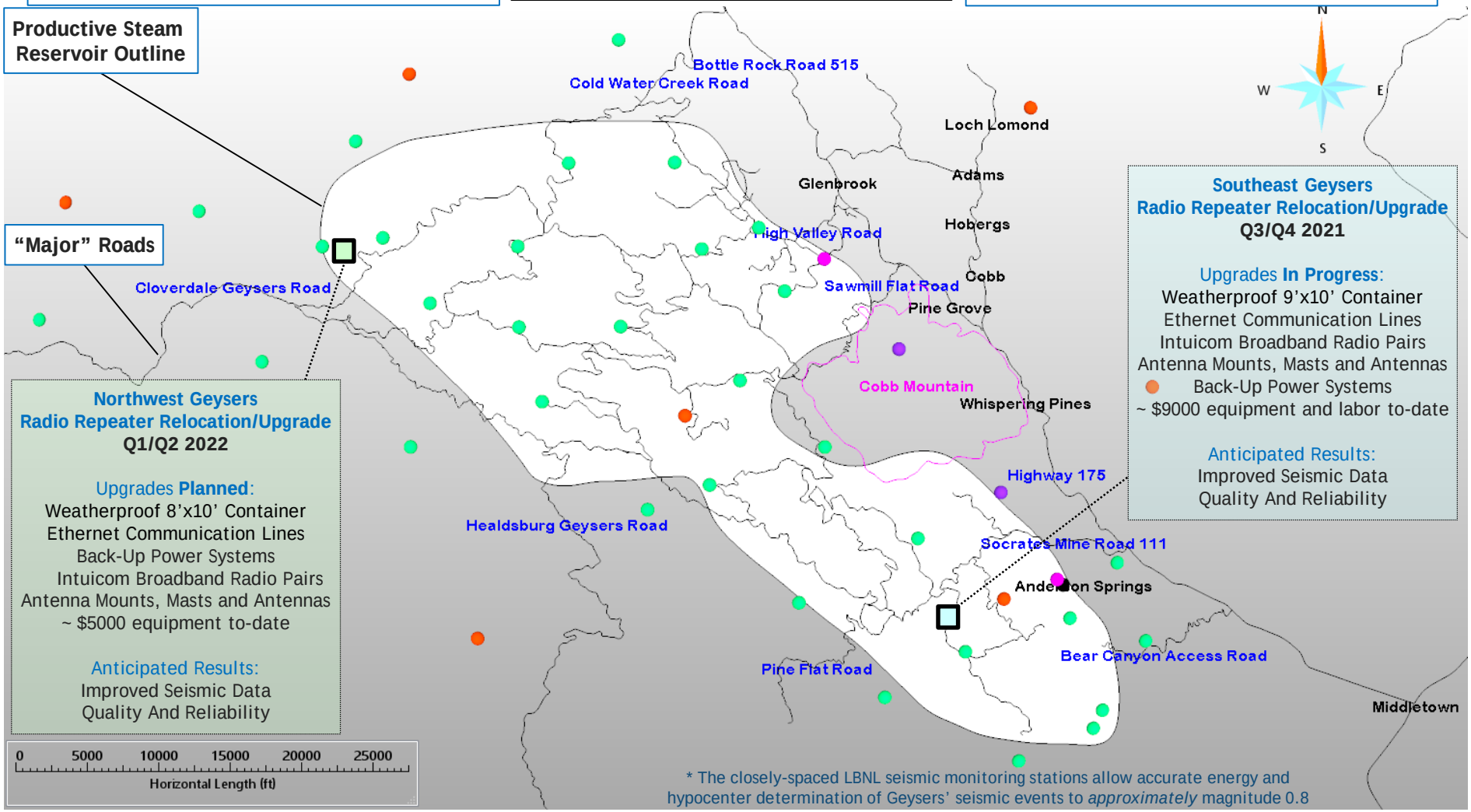
- Seismic Monitoring Networks
  - USGS / Northern California Seismic Network
  - LBNL / Geysers Power Company Seismic Monitoring Network
  - LBNL / Geysers Power Company Strong Motion Network
- Fieldwide Seismicity Analysis
- Strong Motion Data Analysis
  - Peak Ground Acceleration
  - Energy / Distance / Modified Mercalli Intensity
  - Community Hotline
- Water Injection and Induced Seismicity Animations
- Calpine 3D Structural Model Status
  - Fracture / Fault Analysis
  - Local Seismicity Analysis
  - 3D Pre-Drilling Project Analysis (Well Planning)

# Geysers Geothermal Field, Nearby Communities and Seismic Monitoring Networks

**Lawrence Berkeley National Laboratory**
**2003 installation; continuing upgrades**
**34 stations**
Magnitude 0.8 Threshold *
Primary Contacts: Dr. Seiji Nakagawa
Dr. Ernie Majer

**Strong Motion Accelerometers**
**2017/18 Nanometrics installation (2)**
**2020 Q1 Nanometrics installation (2)**
0.1% of Gravitational Acceleration Threshold
Primary Contacts: Ramsey Haught
Jarpe Data Solutions

**US Geological Survey Regional Network**
**1970's installation; several upgrades**
**7 contributing stations**
Magnitude 1.5 Threshold *
Primary Contacts: Dr. Lind Gee / Lynn Dietz
Dr. David Oppenheimer




**Northwest Geysers**
**Radio Repeater Relocation/Upgrade**
**Q1/Q2 2022**

Upgrades **Planned**:
Weatherproof 8'x10' Container
Ethernet Communication Lines
Back-Up Power Systems
Intuicom Broadband Radio Pairs
Antenna Mounts, Masts and Antennas
~ $5000 equipment to-date

Anticipated Results:
Improved Seismic Data
Quality And Reliability

**Southeast Geysers**
**Radio Repeater Relocation/Upgrade**
**Q3/Q4 2021**

Upgrades **In Progress**:
Weatherproof 9'x10' Container
Ethernet Communication Lines
Intuicom Broadband Radio Pairs
Antenna Mounts, Masts and Antennas
Back-Up Power Systems
~ $9000 equipment and labor to-date

Anticipated Results:
Improved Seismic Data
Quality And Reliability

* The closely-spaced LBNL seismic monitoring stations allow accurate energy and hypocenter determination of Geysers' seismic events to *approximately* magnitude 0.8

# Seismic Monitoring Advisory Committee Meeting

**VIDEO**: Cumulative Water Injection And Seismicity Animation; Half-Year Interval From January 1980 through September 2021

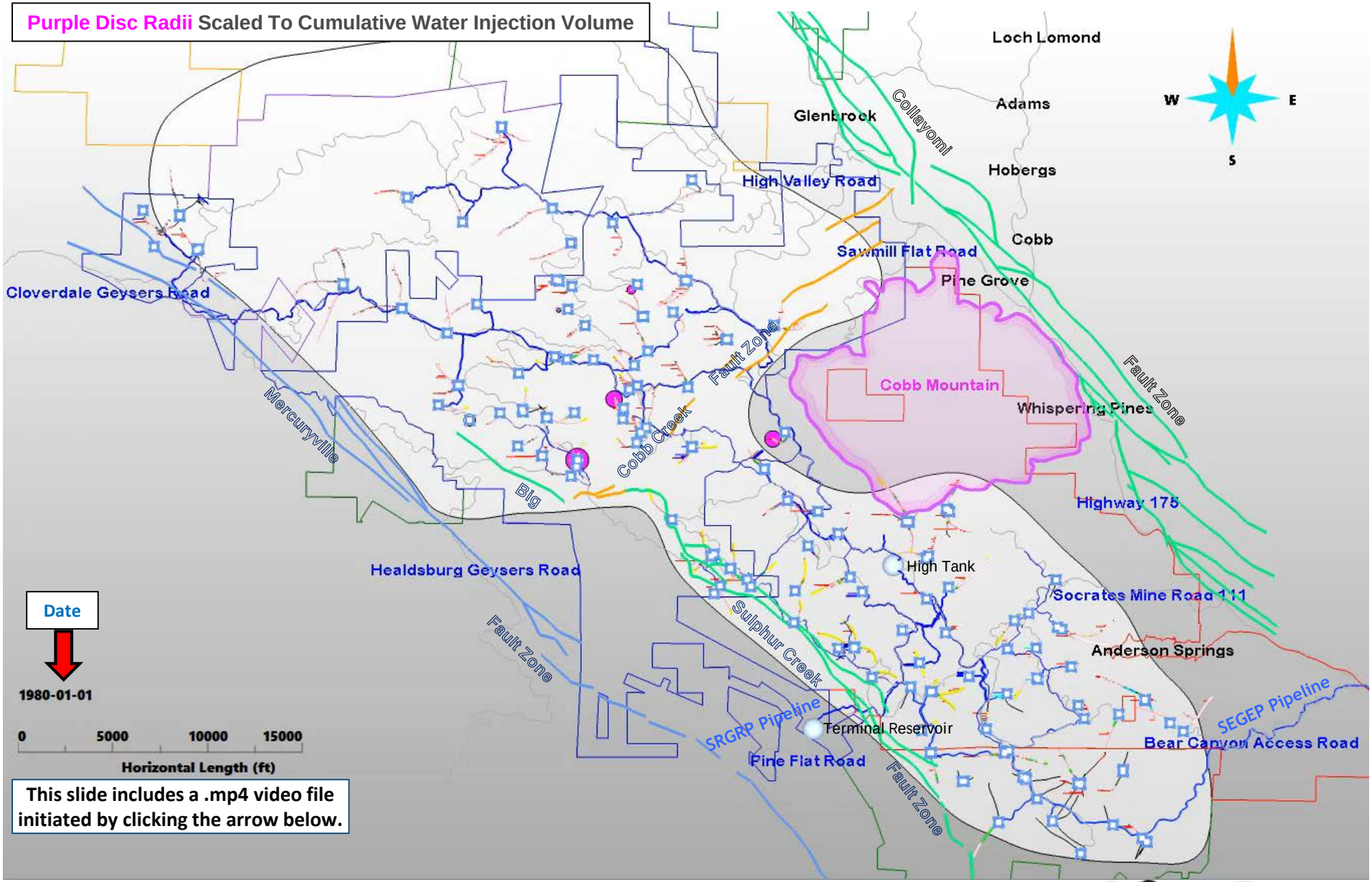
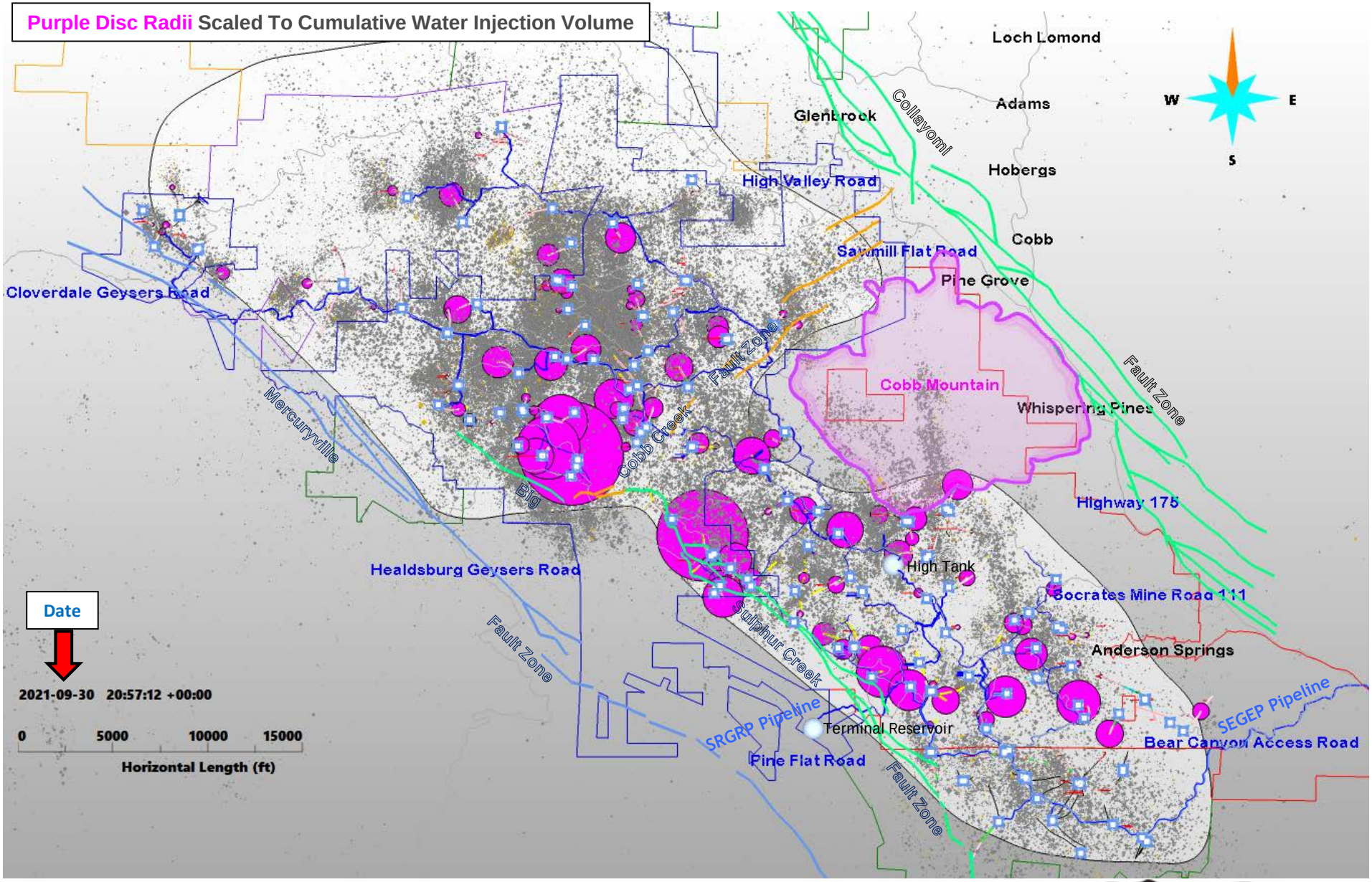


**IMAGE**: Cumulative Water Injection And Induced Seismicity From January 1980 through September 2021



# Seismic Monitoring Advisory Committee Meeting

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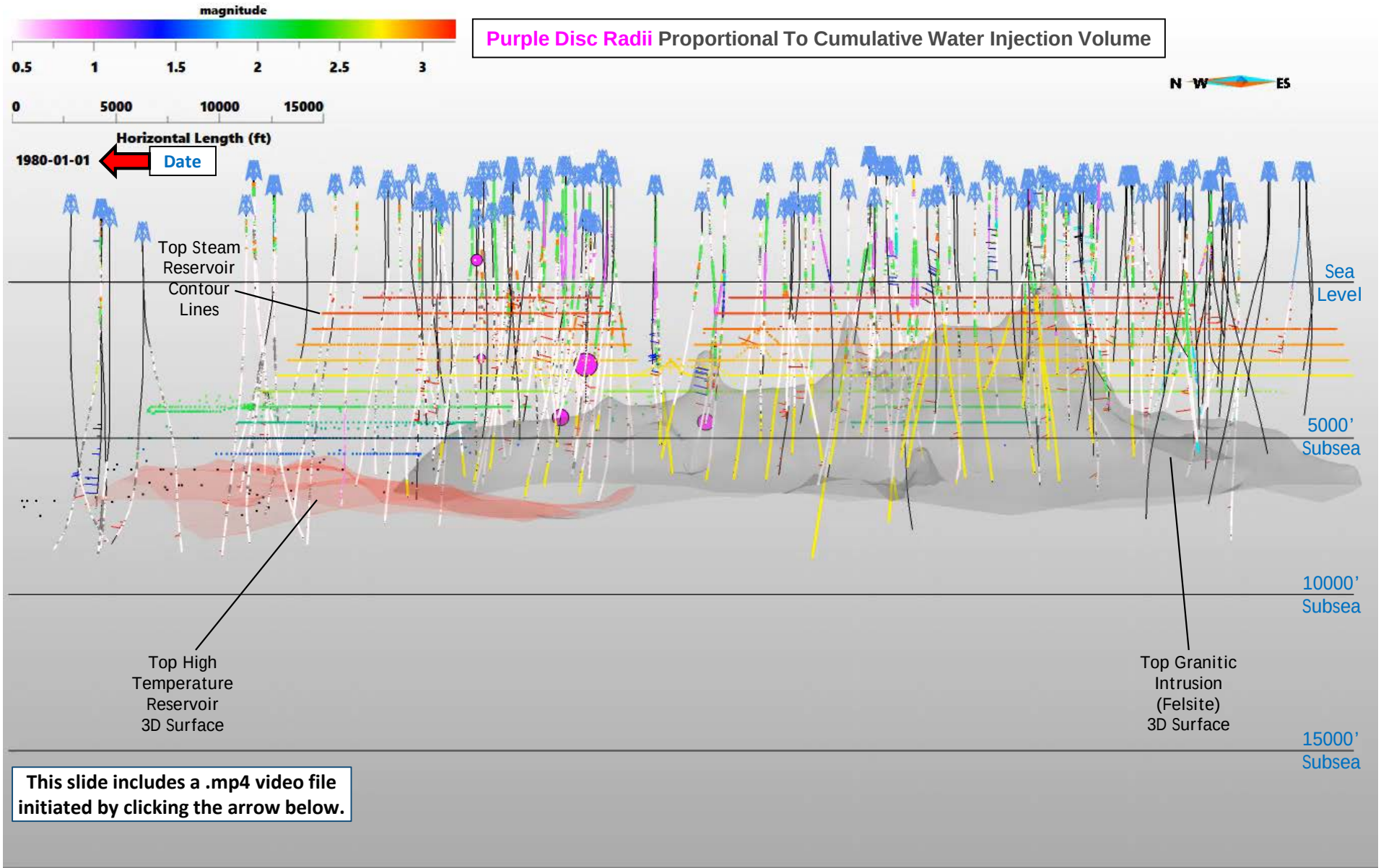
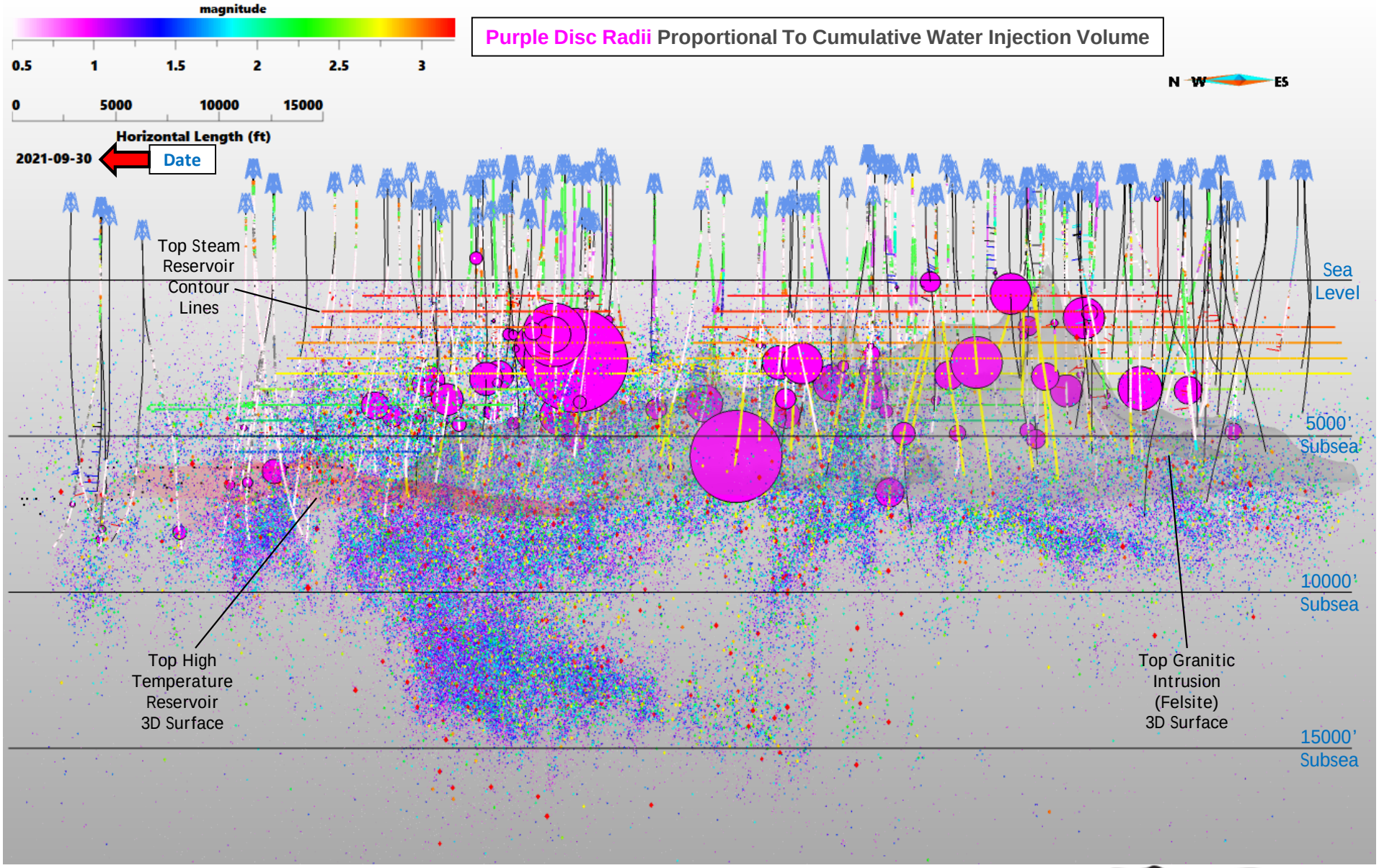


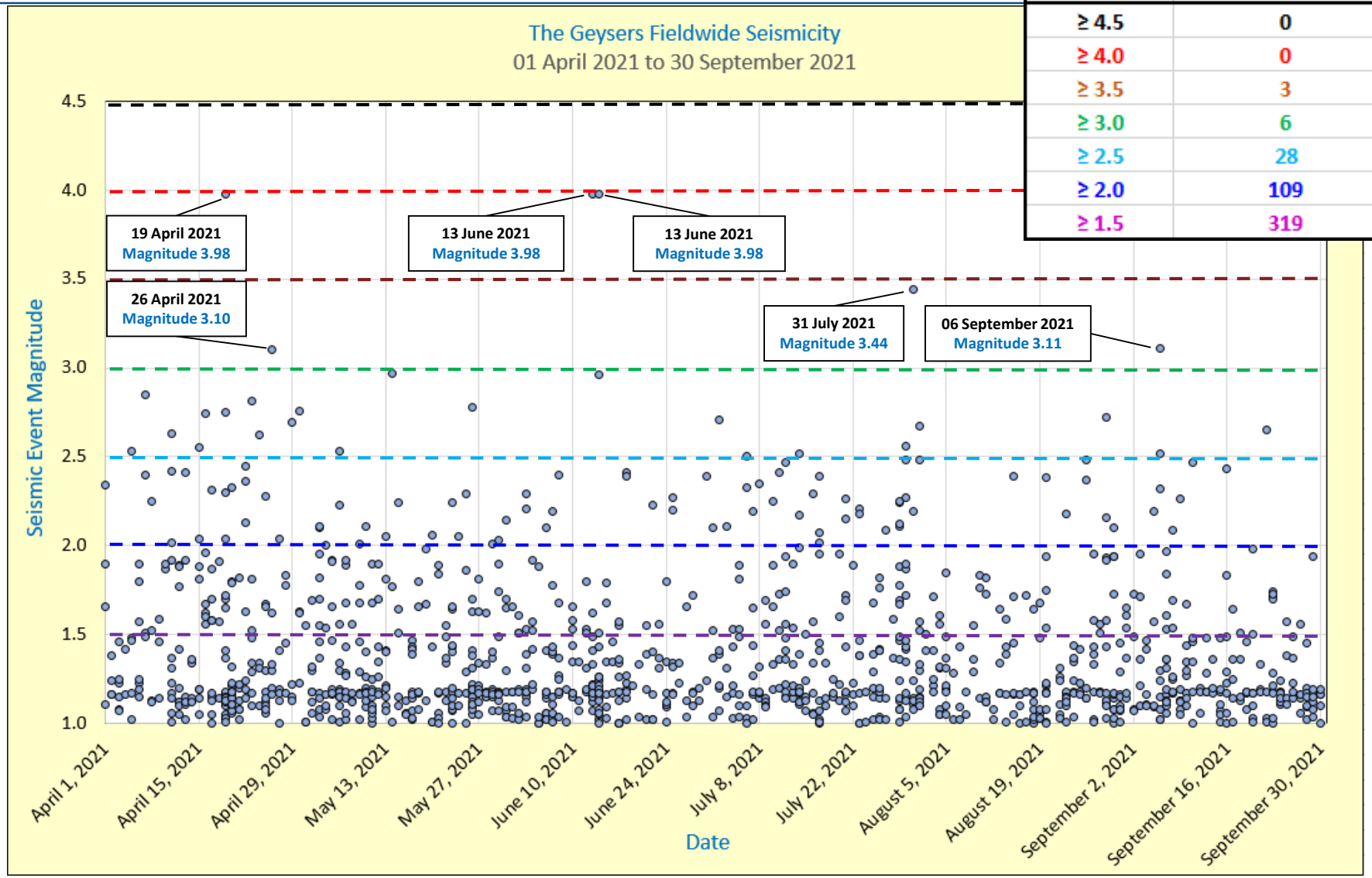
**IMAGE**: Cumulative Water Injection And Induced Seismicity From January 1980 through September 2021



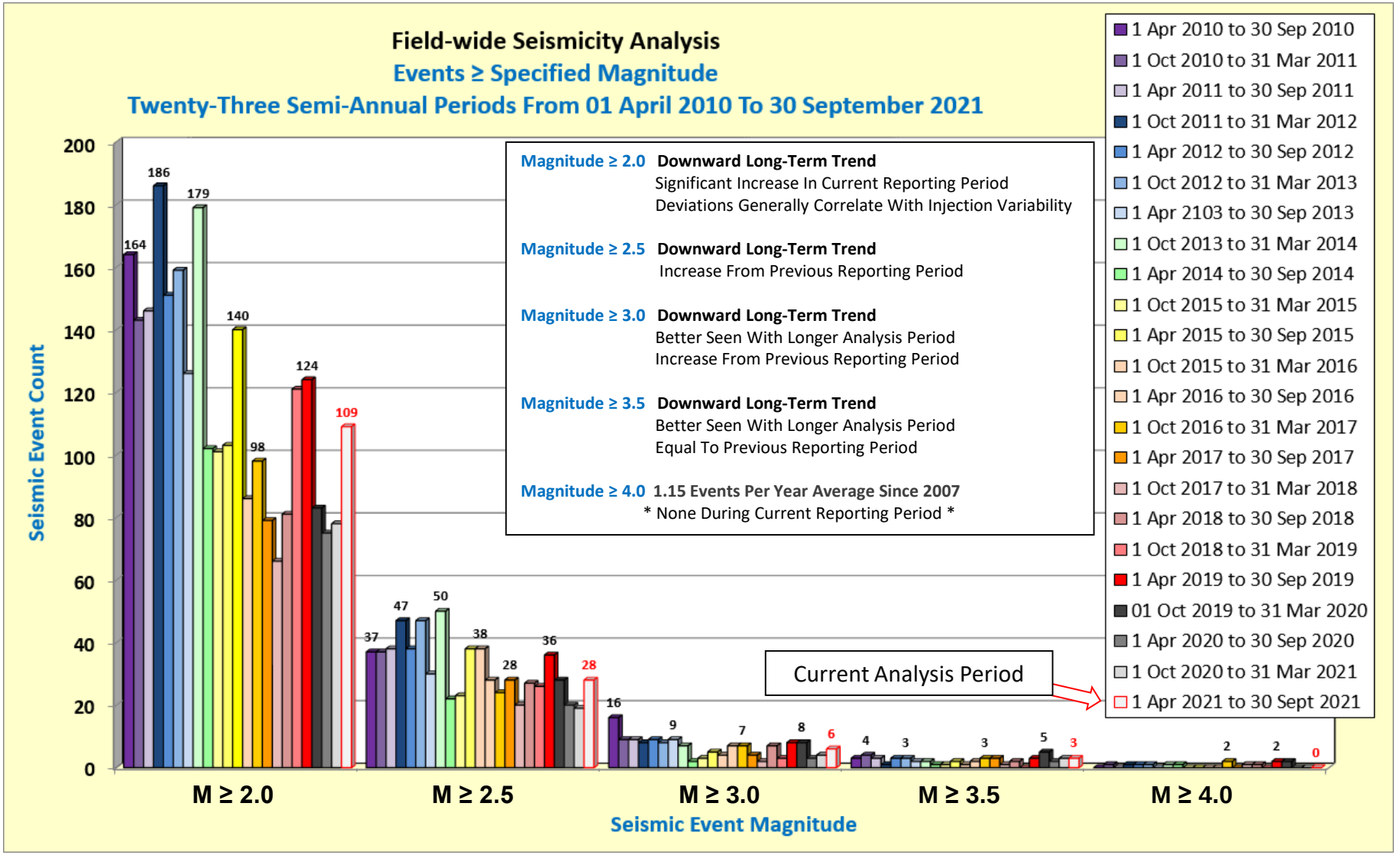
# Seismic Monitoring Advisory Committee Meeting

## Field-wide Seismicity Analysis From 01 April 2021 to 30 September 2021

| Magnitude | Number Of Events |
|---|---|
| ≥ 4.5 | 0 |
| ≥ 4.0 | 0 |
| ≥ 3.5 | 3 |
| ≥ 3.0 | 6 |
| ≥ 2.5 | 28 |
| ≥ 2.0 | 109 |
| ≥ 1.5 | 319 |



# Field-wide Seismicity Analysis
## Comparison of Twenty-Two Semi-Annual Reporting Periods Since 01 April 2010



# Seismic Monitoring Advisory Committee Meeting

## Monthly Field-wide Water Injection By Water Source And Magnitude ≥ 4.0 Seismicity

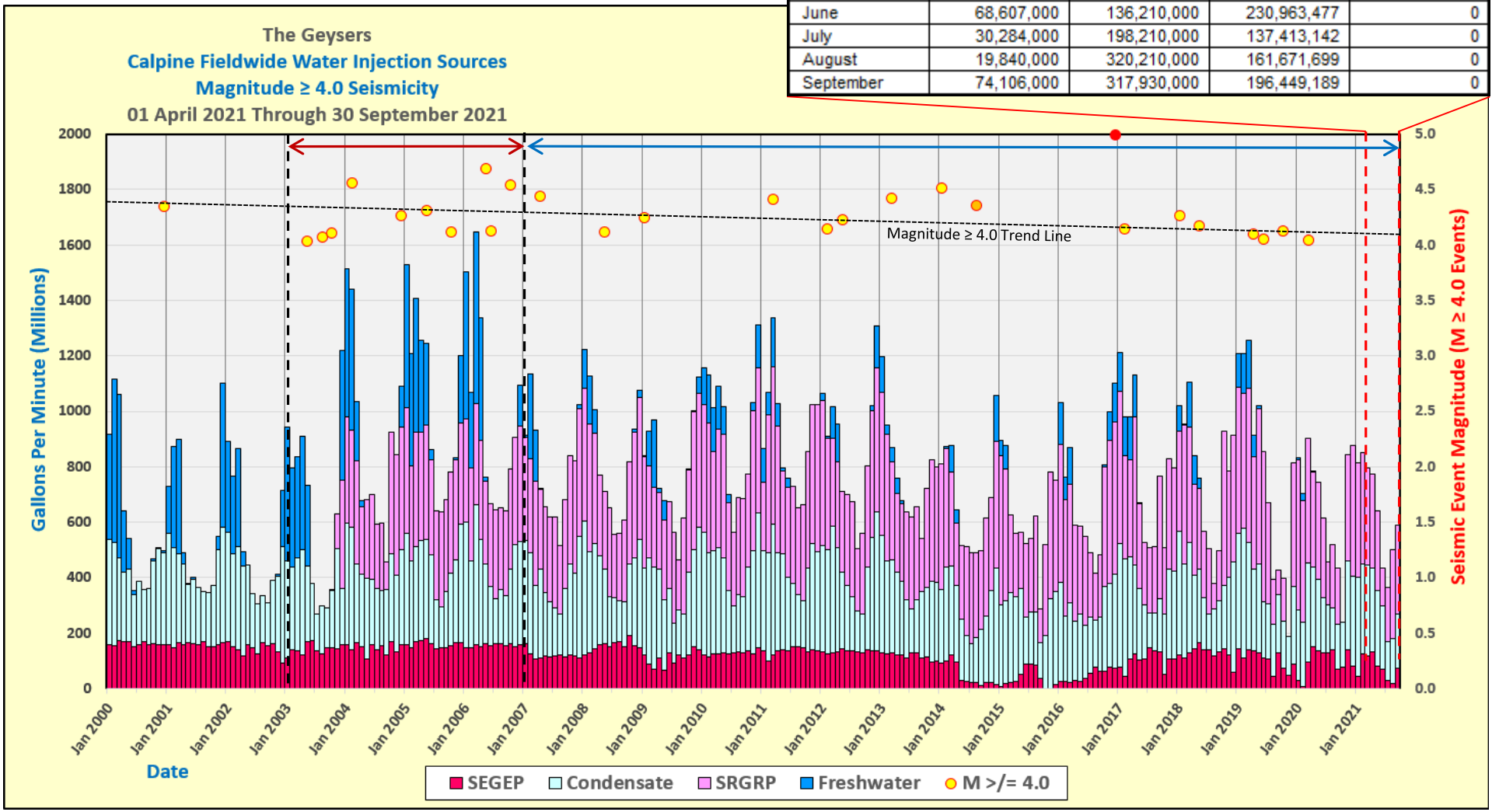
Average Number of Magnitude ≥ 4.0 Events Since January 2007 is 1.15 Per Year

| Time Period | Magnitude ≥ 4.0 Seismic Events |
|---|---|
| January 2003 through December 2006 | 2.50 per year |
| January 2007 through September 2021 | 1.15 per year |

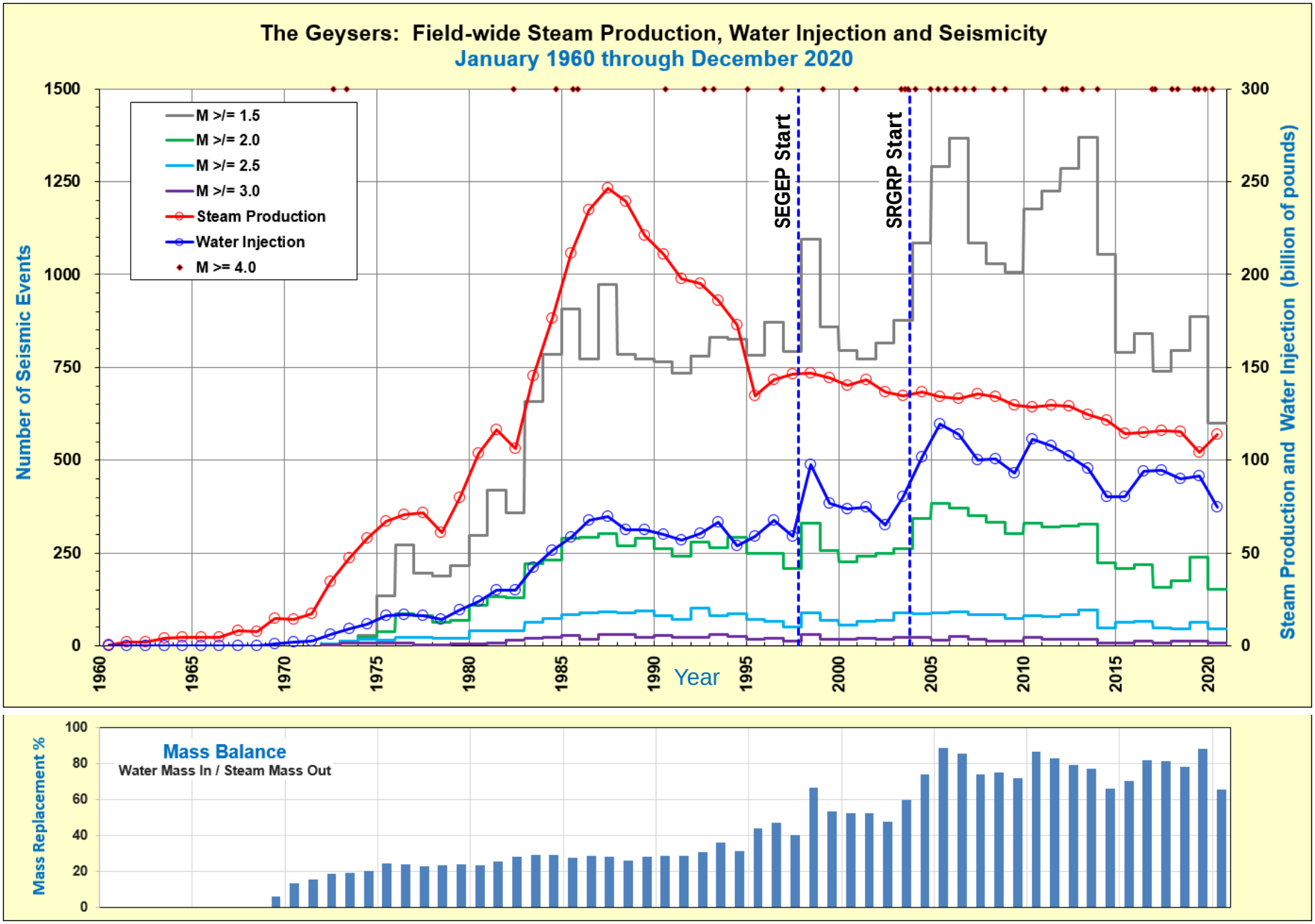
**Water Supply for Reporting Period (Six Months)**

**Water Injection Sources (Gallons)**

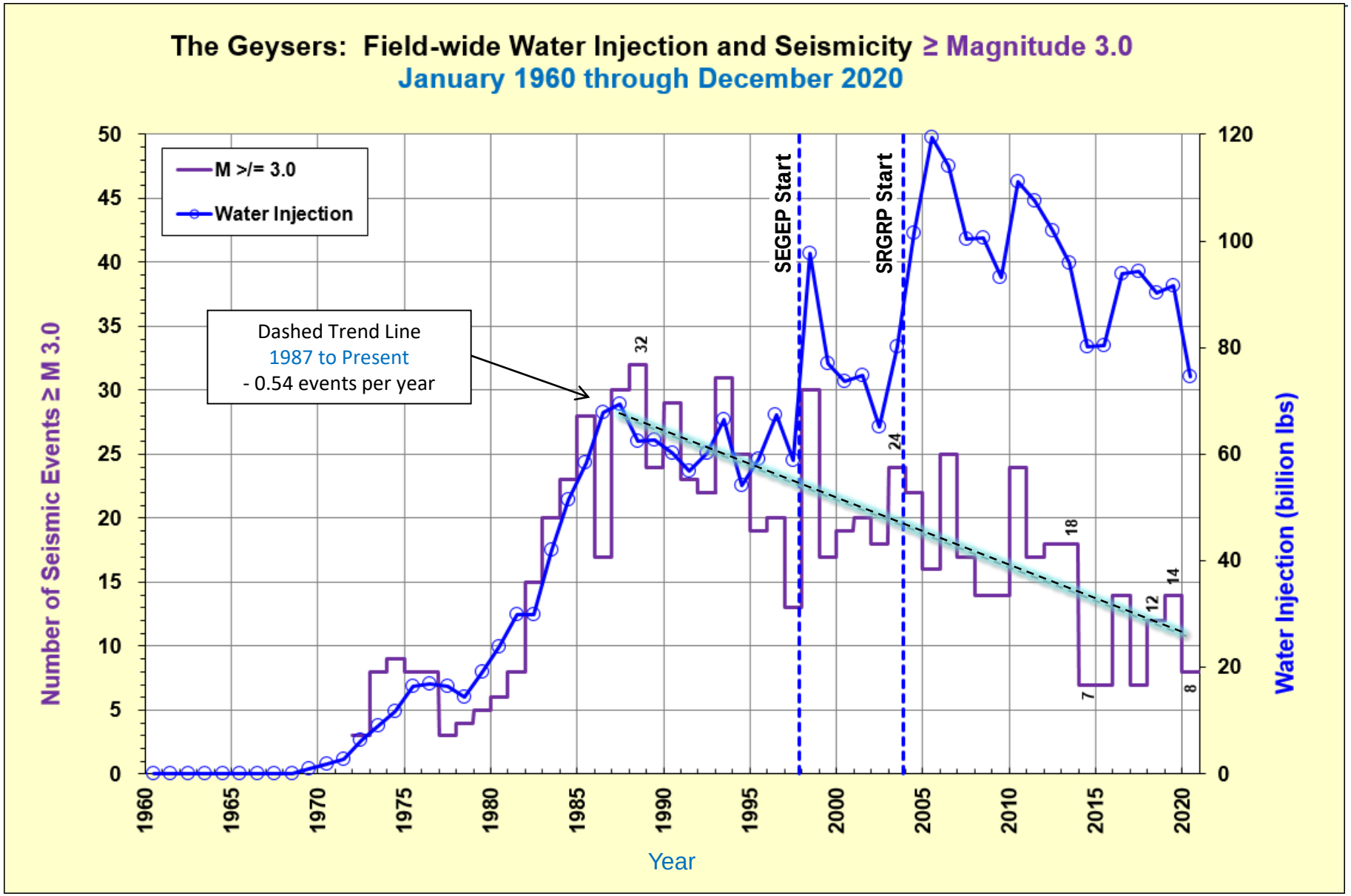
| Month | SEGEP | SRGRP | Condensate | Fresh Water |
|---|---|---|---|---|
| April | 131,339,000 | 339,770,000 | 302,480,229 | 0 |
| May | 82,259,000 | 286,690,000 | 271,970,221 | 0 |
| June | 68,607,000 | 136,210,000 | 230,963,477 | 0 |
| July | 30,284,000 | 198,210,000 | 137,413,142 | 0 |
| August | 19,840,000 | 320,210,000 | 161,671,699 | 0 |
| September | 74,106,000 | 317,930,000 | 196,449,189 | 0 |



Yearly Field-wide Steam Production, Water Injection and Seismicity

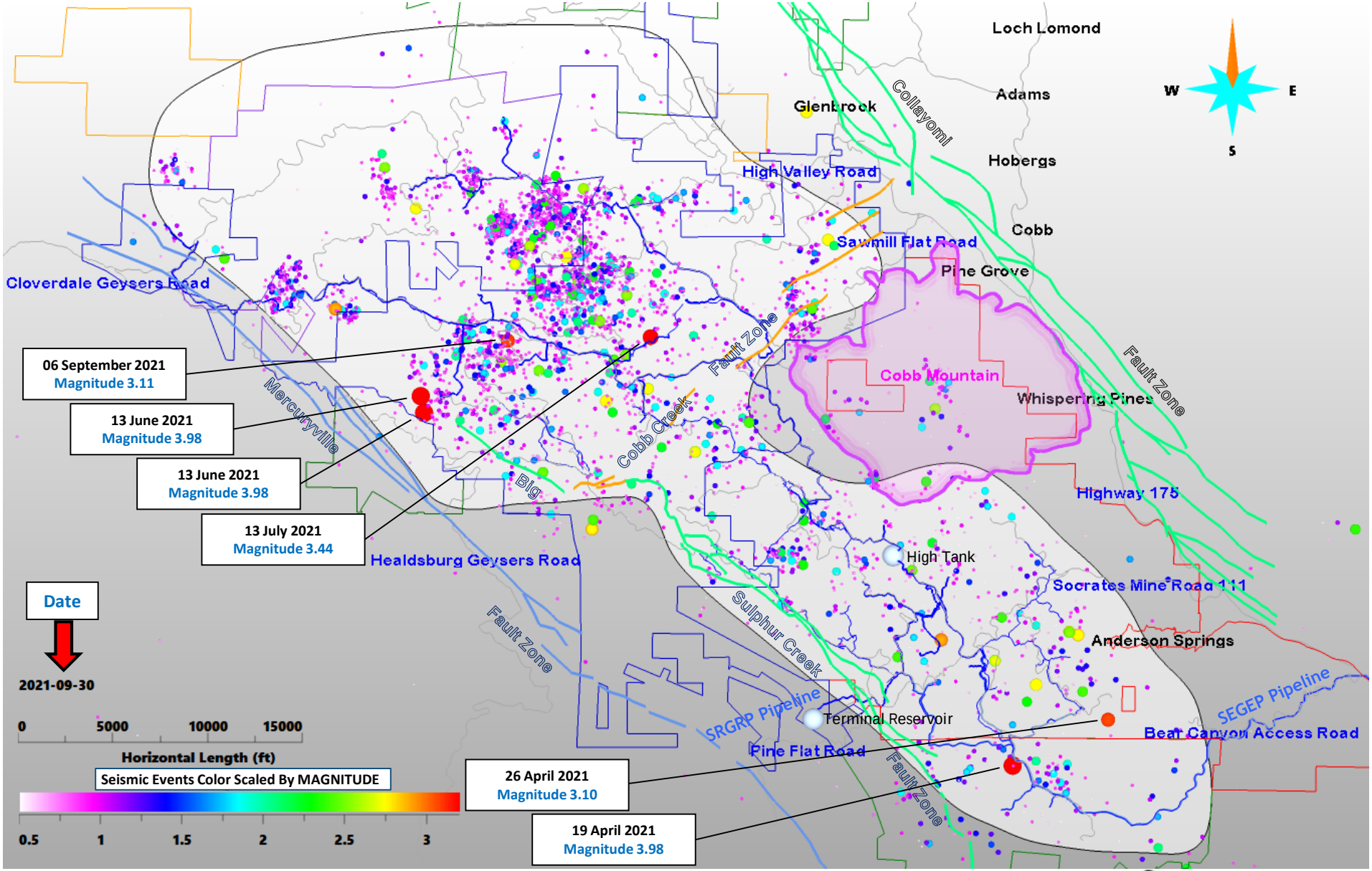


Yearly Field-wide Water Injection and Seismicity ≥ Magnitude 3.0



# Seismic Monitoring Advisory Committee Meeting

## Field-wide Seismicity Animation At Two Week Interval



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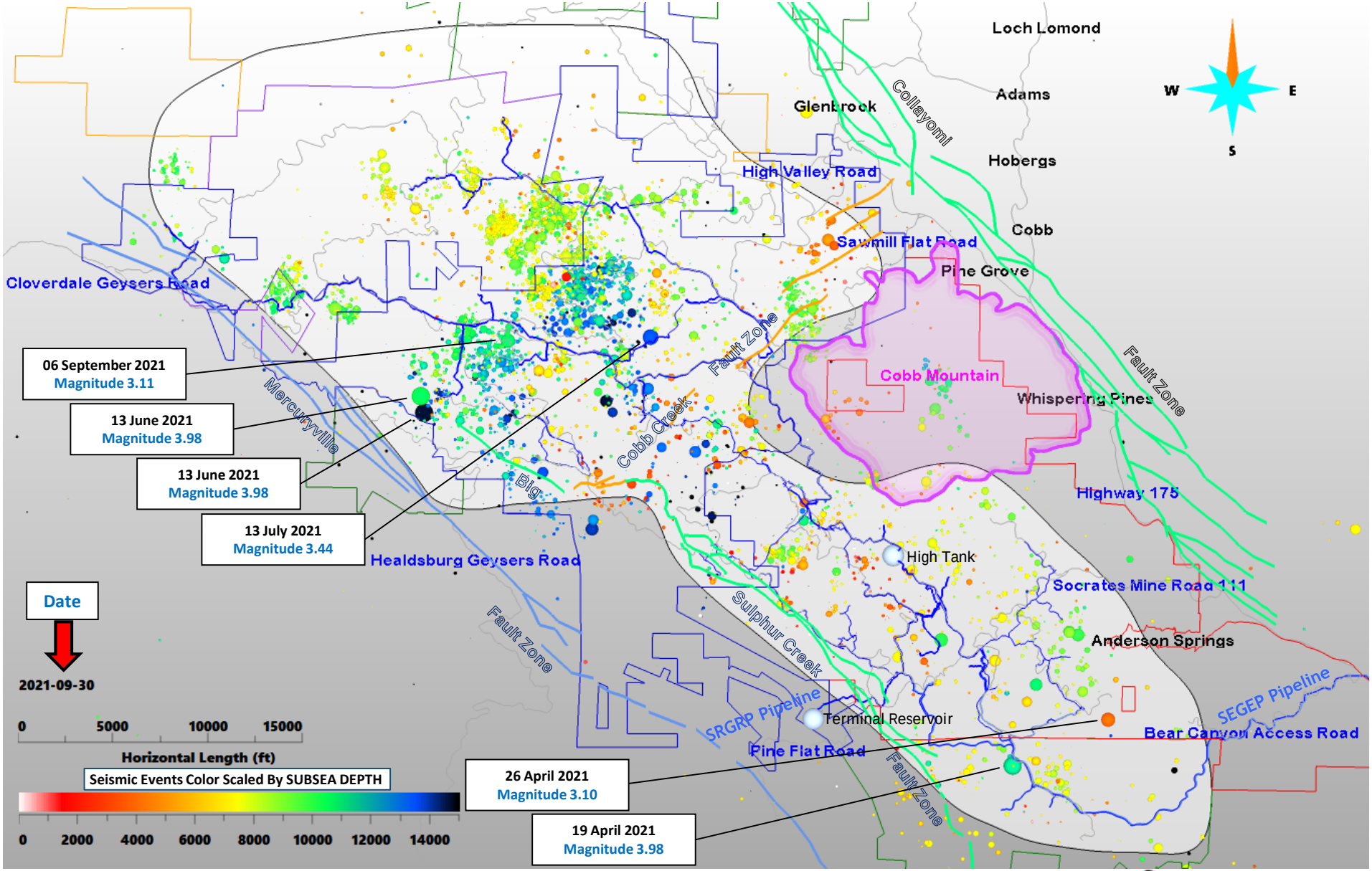
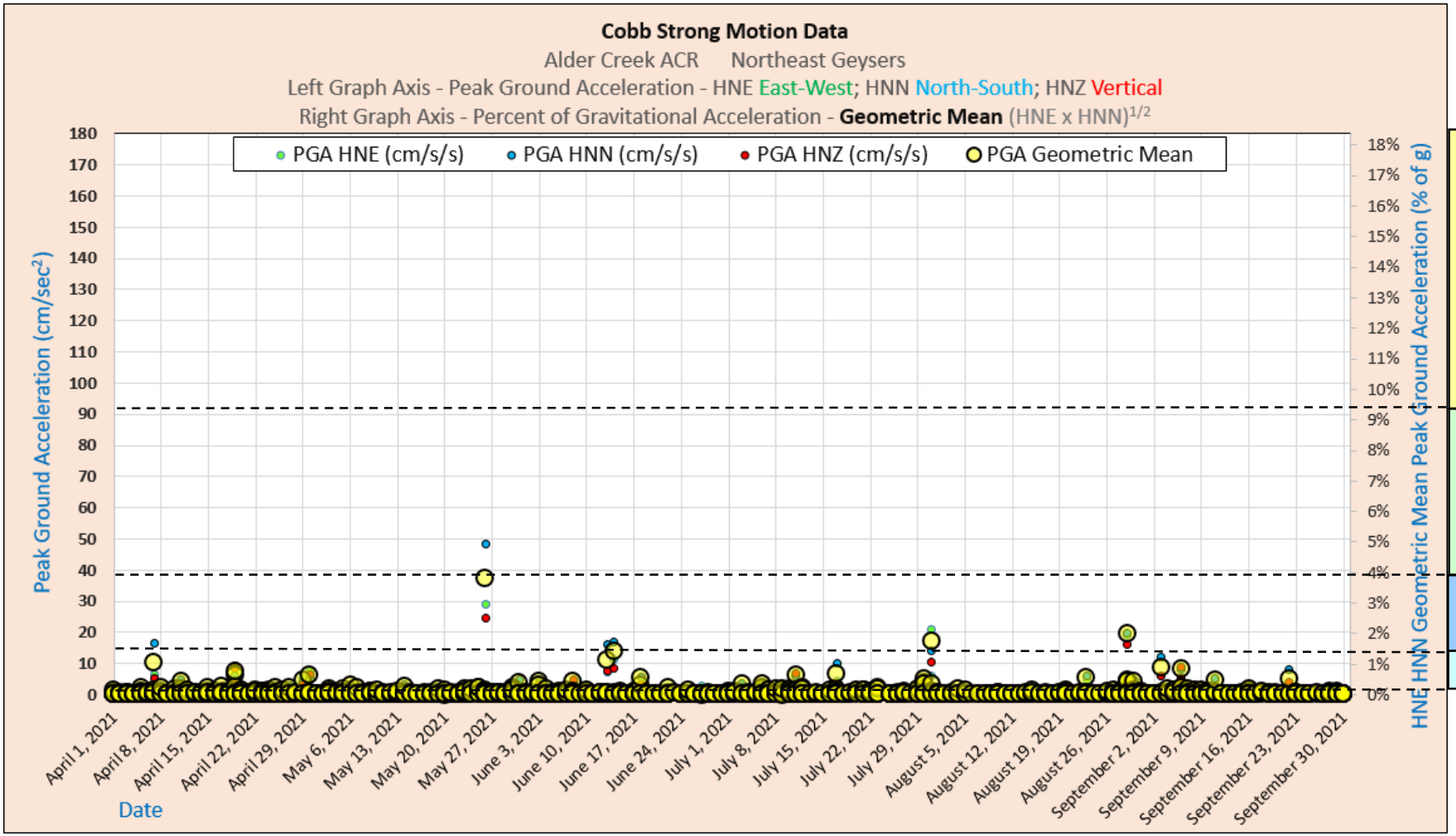


# Cobb Area: Strong Motion Determinations At Alder Creek Strong Motion Station




| 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 |

# Southeast Geysers Seismicity From 16 April 2021 Through 26 April 2021

For the reporting period from 01 October 2021 through 31 March 2021 the results of the water injection and induced seismicity analysis were very encouraging.

However, in the first month of the current reporting period, there were three relatively large seismic events occurred on Calpine leases to the west of Anderson Springs:

- 16 April 2021 Magnitude 2.74
- 23 April 2021 Magnitude 2.81
- 24 April 2021 Magnitude 2.62

Additional concern arose due to two relatively large events that occurred within the NCPA leases:

- 19 April 2021 Magnitude 3.98
- 26 April 2021 Magnitude 3.10

**Note**: Recent USGS Tomographic Double-Difference Seismicity Hypocenter Determinations Reposition This Event Slightly Northward and Within The Calpine Lease.

Events greater than magnitude 2.60 occur infrequently in the southeast Geysers and resulted in 19 community hotline calls. Return calls to community leaders were completed in several cases - and attempted multiple times for the remainder - to discuss the scientific and public relations issues associated with these events.

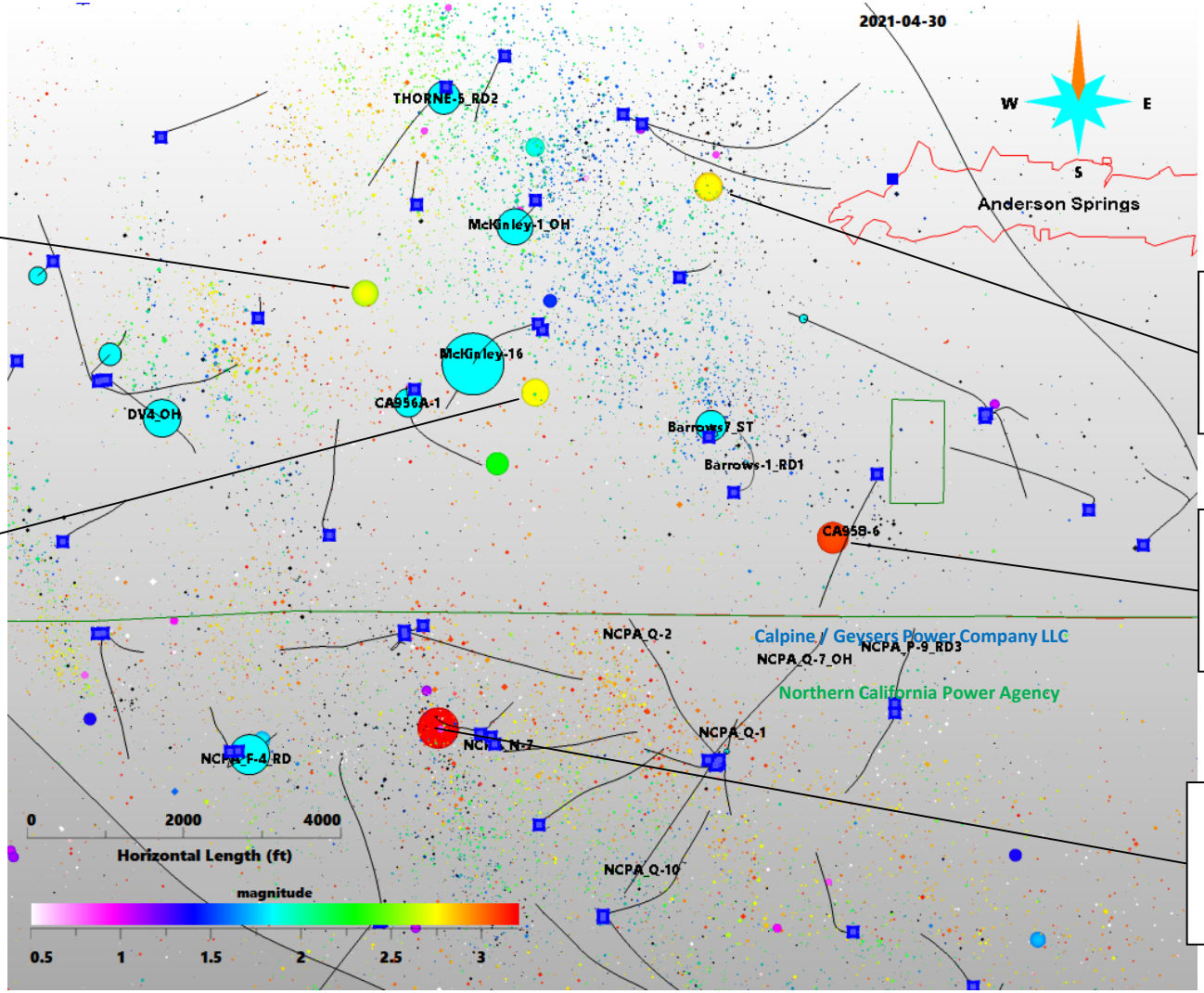
**The 16 April 2021 to 26 April 2021 seismicity is discussed in detail within the following slides.**

| 16 April 2021 | 19 April 2021 | 23 April 2021 | 24 April 2021 | 26 April 2021 |
|---|---|---|---|---|
| Magnitude 2.74 | Magnitude 3.98 | Magnitude 2.81 | Magnitude 2.62 | Magnitude 3.10 |
| 3D Distance 13375' | 3D Distance 15760' | 3D Distance 11475' | 3D Distance 10010' | 3D Distance 8810' |
| Map Distance 5290' | Map Distance 9075' | Map Distance 2145' | Map Distance 7750' | Map Distance 6130' |
| 12.42% of g | 10.38% of g | 12.95% of g | 8.15% of g | 8.20% of g |

# 01 April 2021 to 30 September 2021 Induced Seismicity In Vicinity Of Anderson Springs

**24 April 2021**
Magnitude 2.62
3D Distance 10010'
Map Distance 7750'
8.15% of g
No Calls, But Contributed To Concerns

**16 April 2021**
Magnitude 2.74
3D Distance 13375'
Map Distance 5290'
12.42% of g
One Call

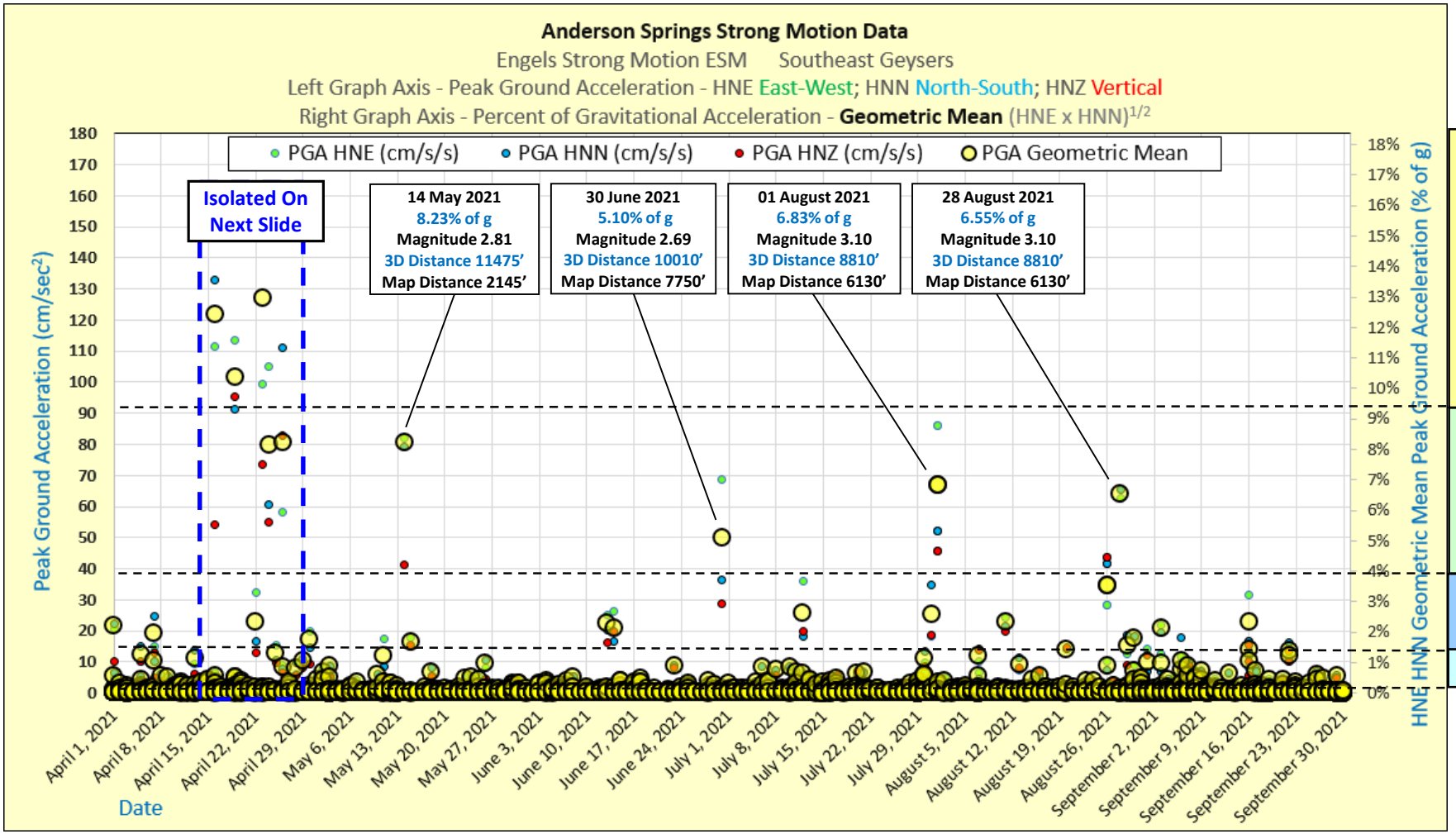



**23 April 2021**
Magnitude 2.81
3D Distance 11475'
Map Distance 2145'
12.95% of g
Five Calls

**26 April 2021**
Magnitude 3.10
3D Distance 8810'
Map Distance 6130'
8.20% of g
Six Calls

**19 April 2021**
Magnitude 3.98
3D Distance 15760'
Map Distance 9075'
10.38% of g
Nine Calls

# Anderson Springs Area: Strong Motion Determinations At Engels Strong Motion Station




| 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 |
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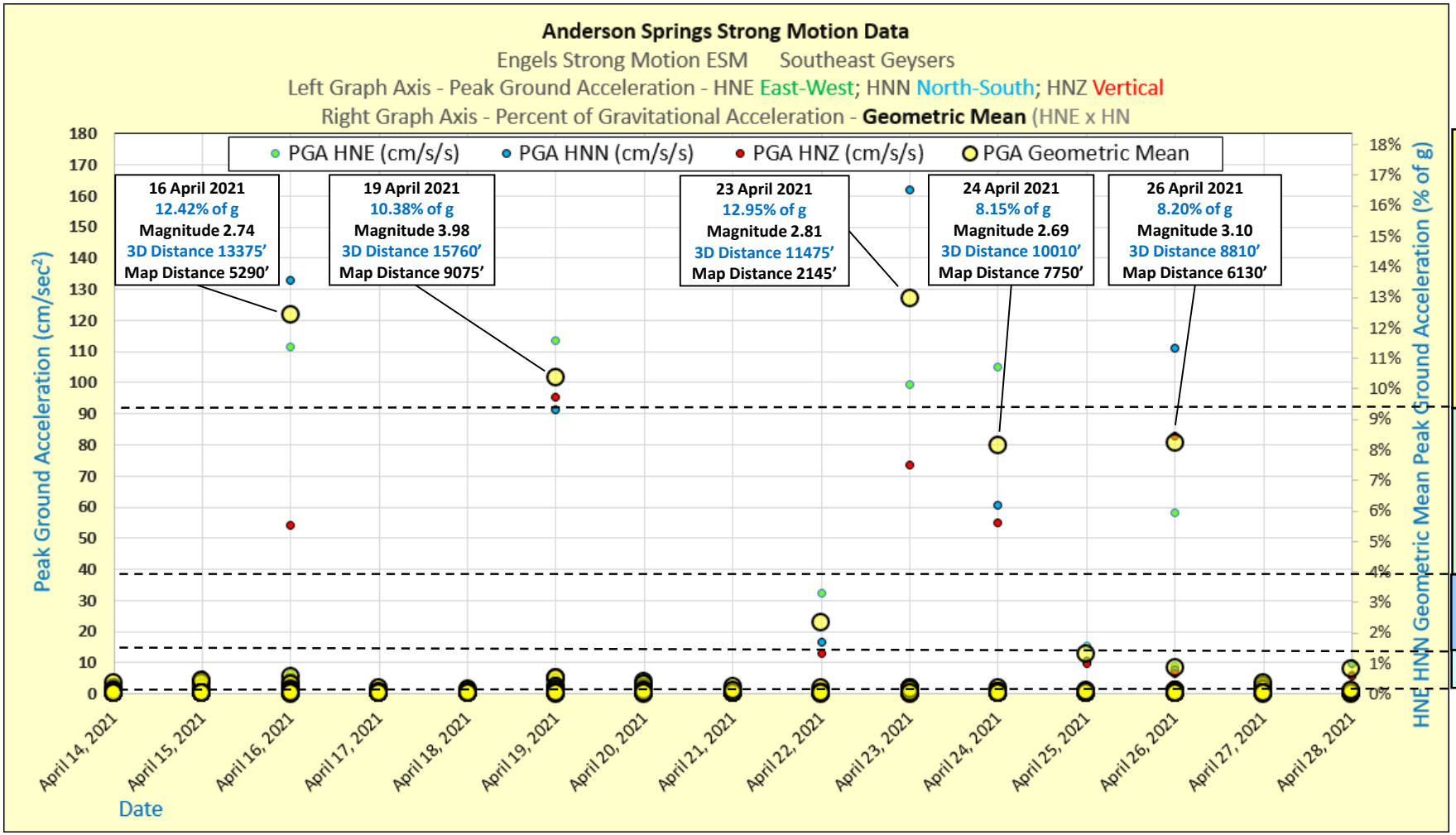
# Anderson Springs Area: Strong Motion Determinations At Engels Strong Motion Station 14-28 APRIL 2021 ONLY

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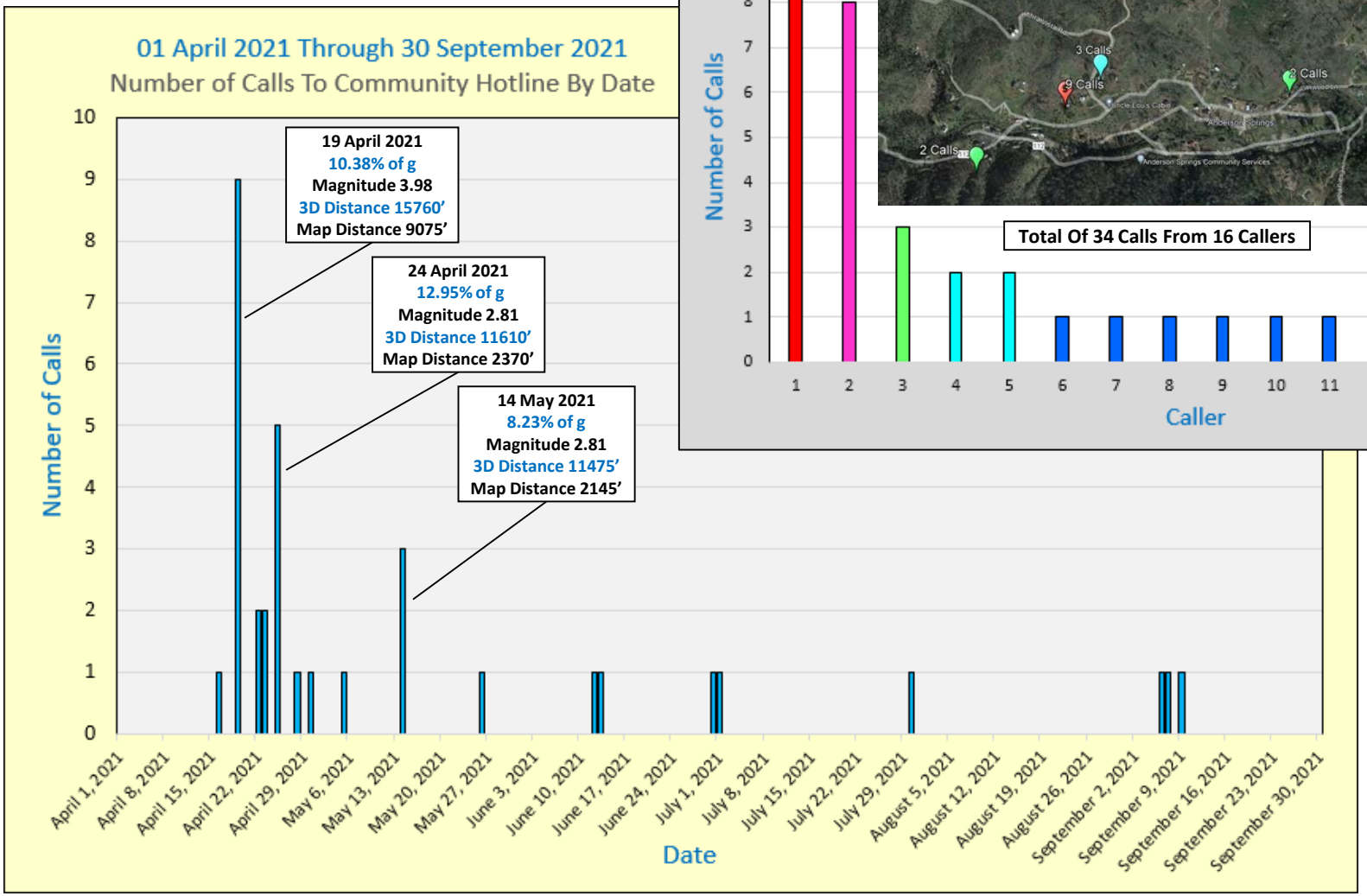
| Modified Mercalli Intensity | I | II-III | IV | V | VI | VII | VIII | IX | X |

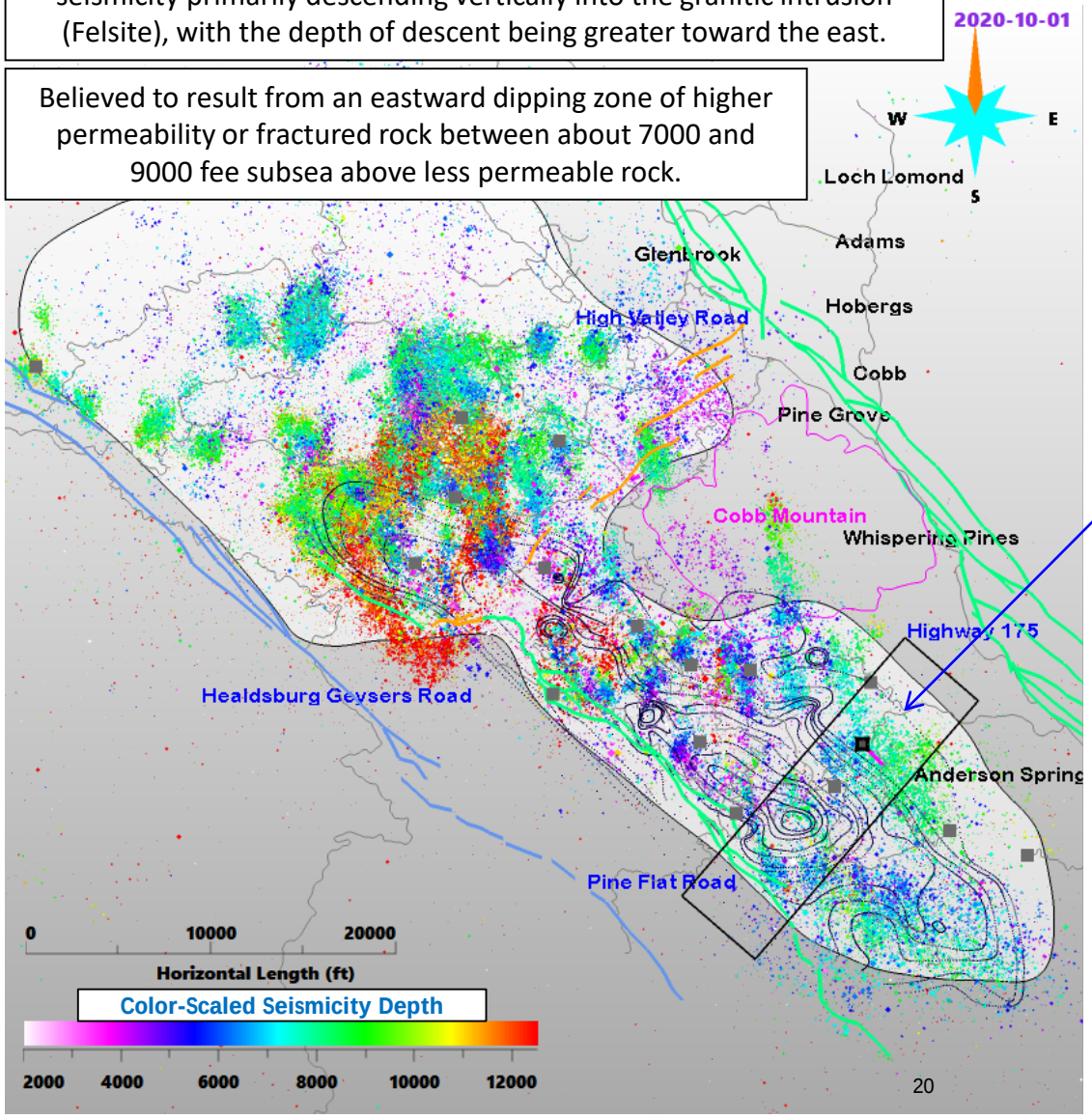
# Community Hotline Statistics

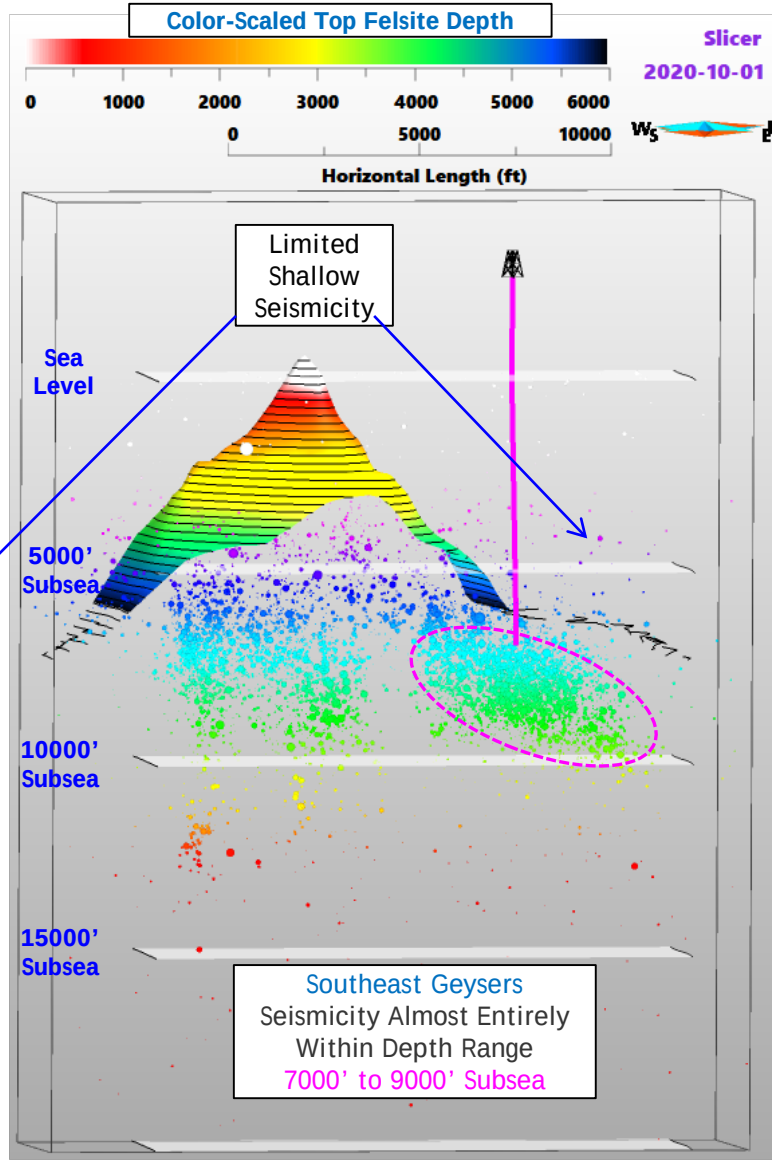


# Seismicity From 01 January 2005 to 01 October 2020 Shown

In the Southeast Geysers, Calpine injection until late 2020 resulted in seismicity primarily descending vertically into the granitic intrusion (Felsite), with the depth of descent being greater toward the east.

Believed to result from an eastward dipping zone of higher permeability or fractured rock between about 7000 and 9000 fee subsea above less permeable rock.



# Seismic Monitoring Advisory Committee Meeting

## Detailed Seismicity Analysis for 01 April 2021 to 30 April 2021 2019 and 2020 Seismicity As Light Gray Symbols 2021 Seismicity Color-Scaled By Magnitude (and 2x Symbol Size)

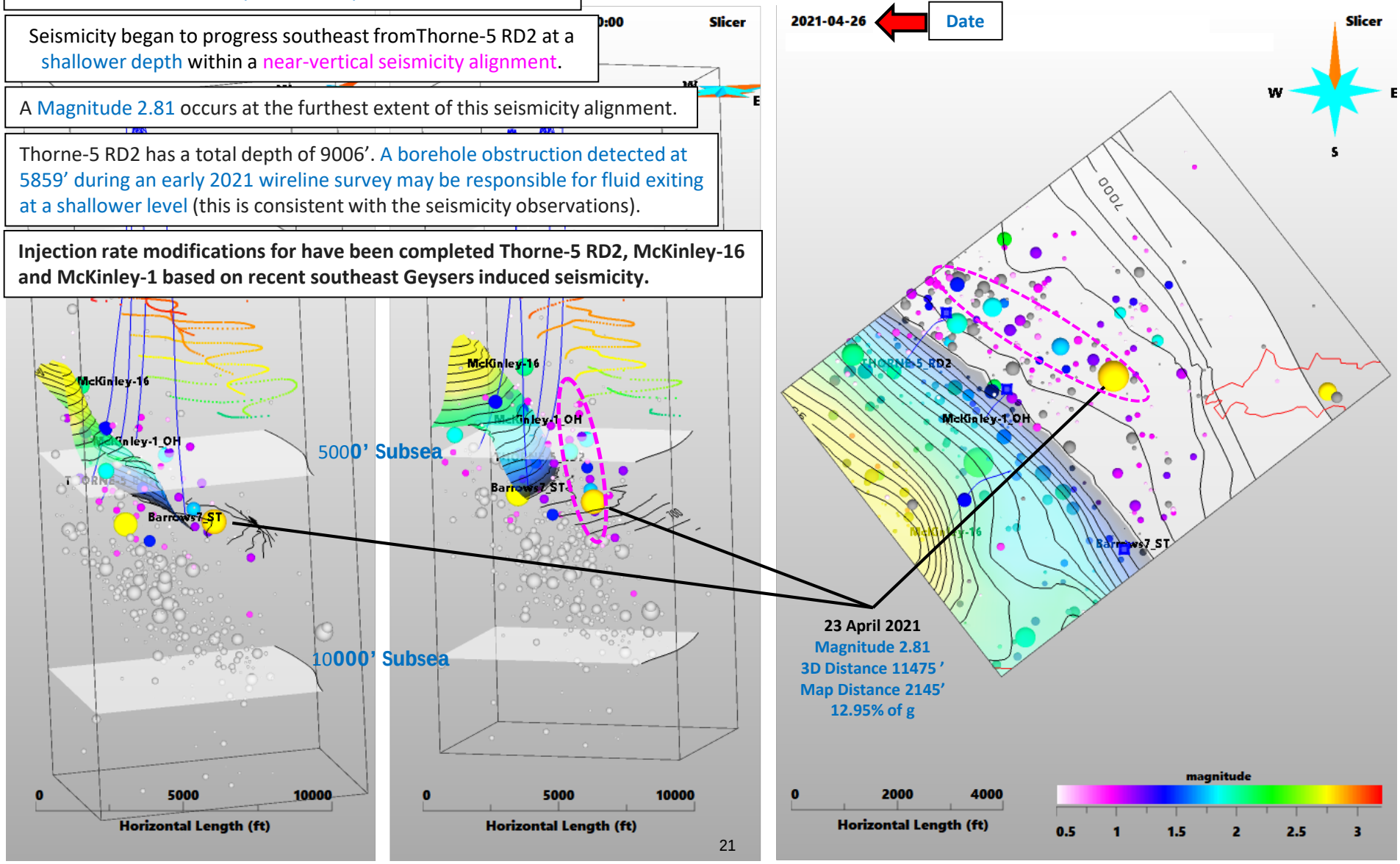
In early 2021 there were increased and variable injection rates at Thorne-5, McKinley-1, McKinely-16 and Barrows-7.

Seismicity began to progress southeast fromThorne-5 RD2 at a shallower depth within a near-vertical seismicity alignment.

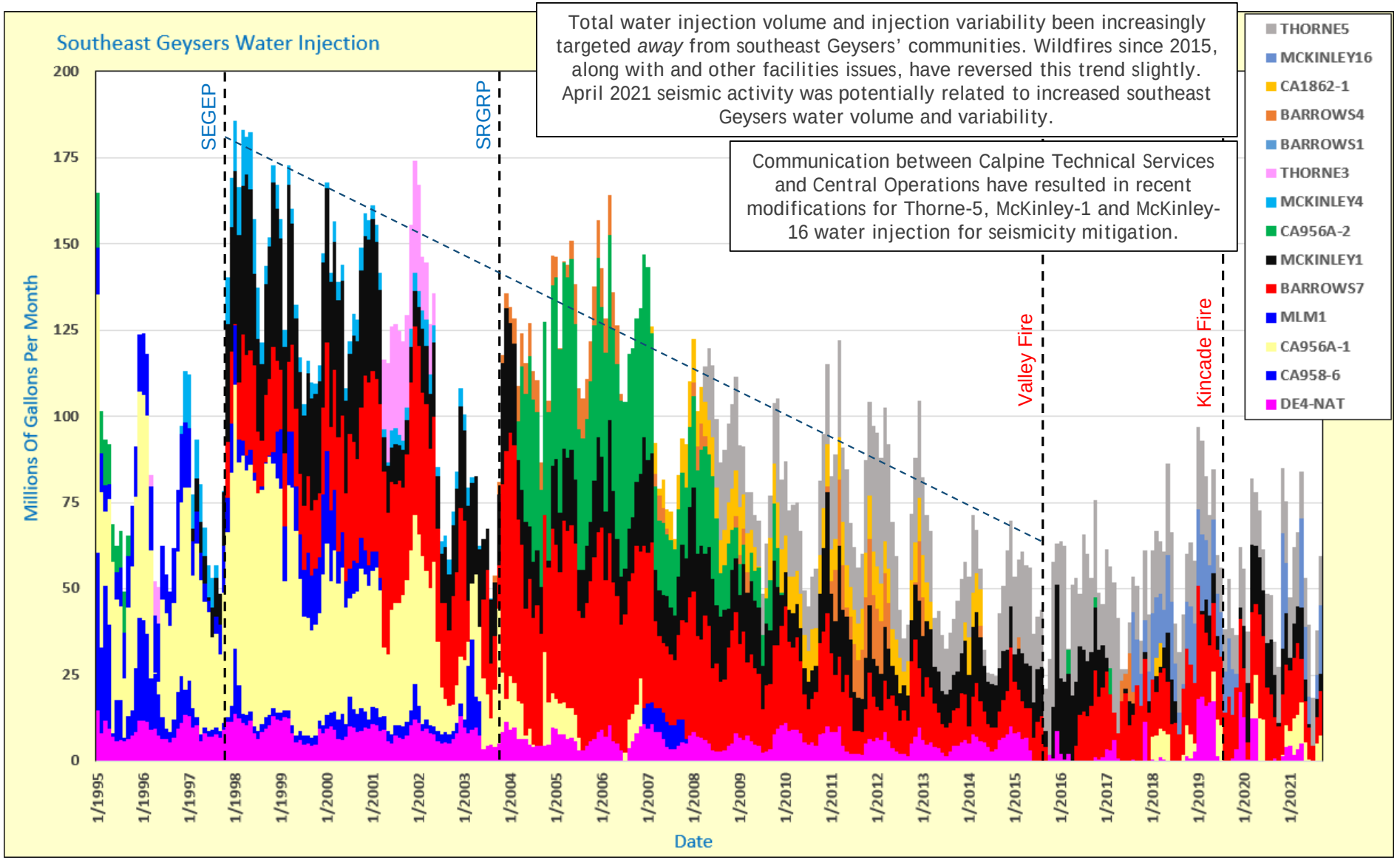
A Magnitude 2.81 occurs at the furthest extent of this seismicity alignment.

Thorne-5 RD2 has a total depth of 9006'. A borehole obstruction detected at 5859' during an early 2021 wireline survey may be responsible for fluid exiting at a shallower level (this is consistent with the seismicity observations).

**Injection rate modifications for have been completed Thorne-5 RD2, McKinley-16 and McKinley-1 based on recent southeast Geysers induced seismicity.**

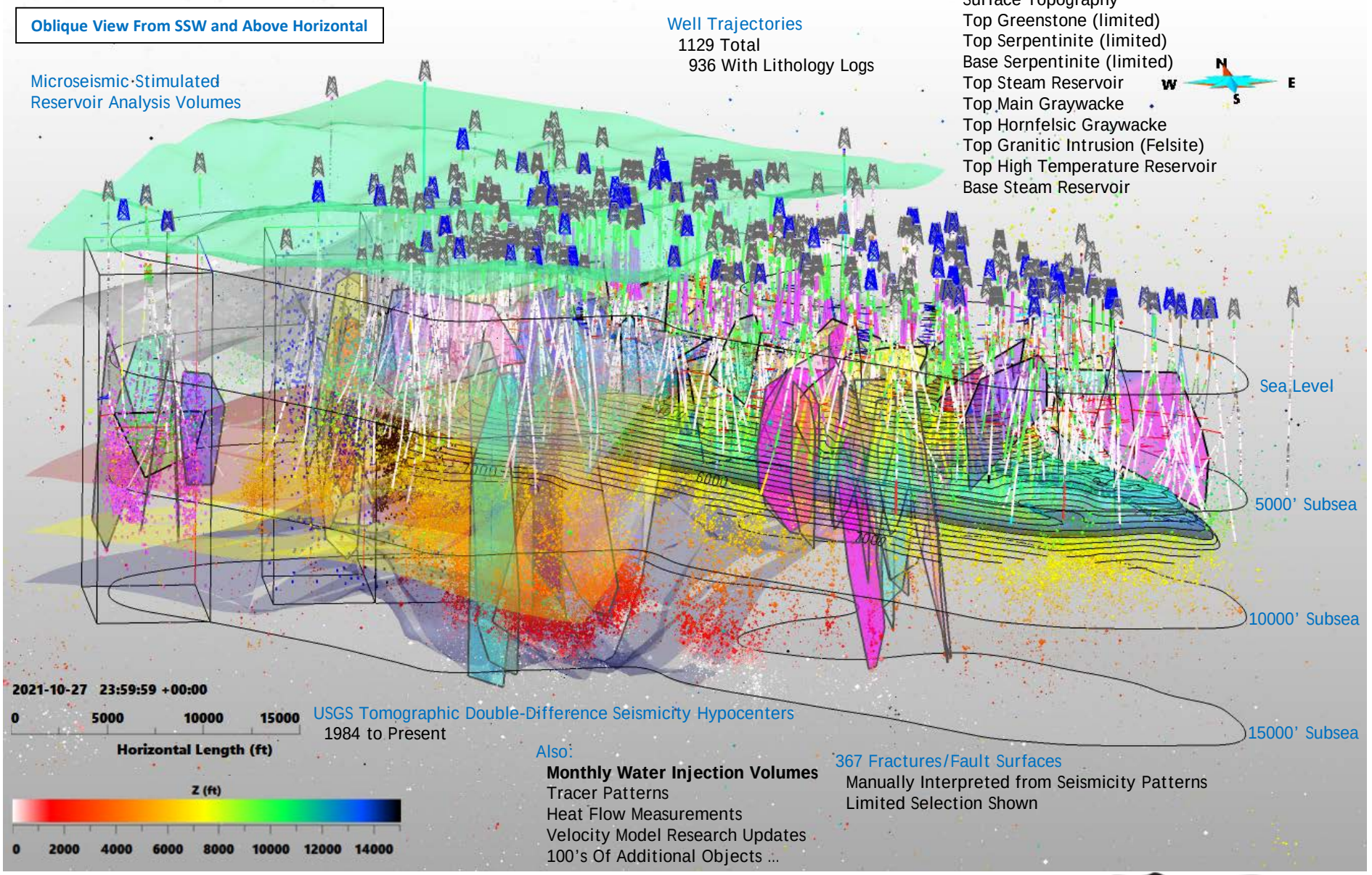


# Southeast Geysers Water Injection Wells January 1995 to September 2021



# Seismic Monitoring Advisory Committee Meeting

## 3D Structural Model Status

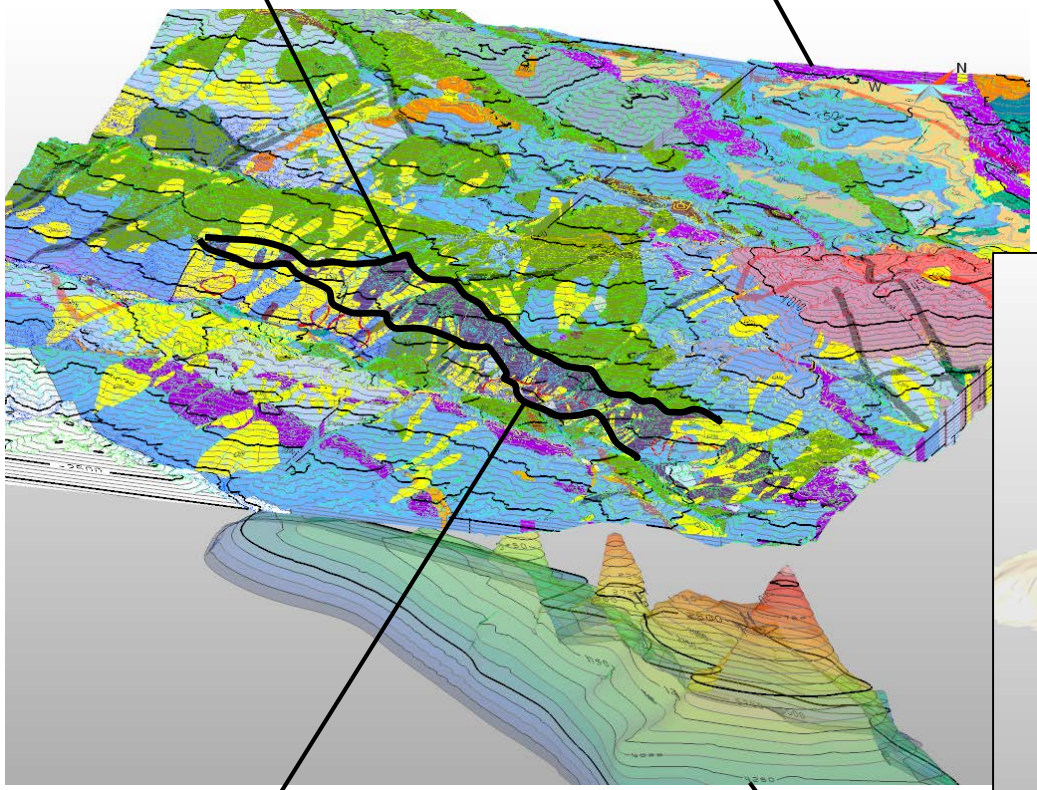


# 3D Structural Model Building

## Model Development Constrained By Lithology Logs and ArcGIS Surface Geologic Map*

ArcGIS Compiled Surface Geology
Imported as Georeferenced Image
Texture Mapped to Topographic Surface

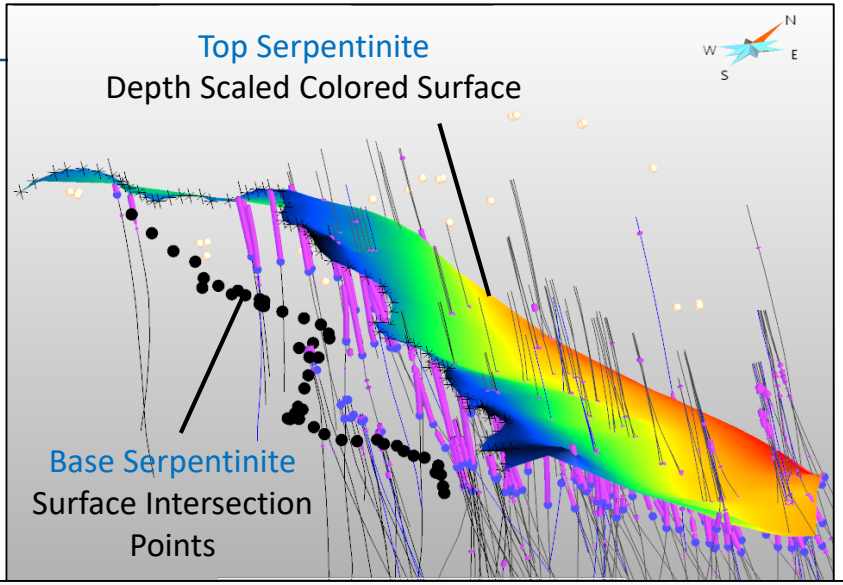
Top Serpentinite Intersection



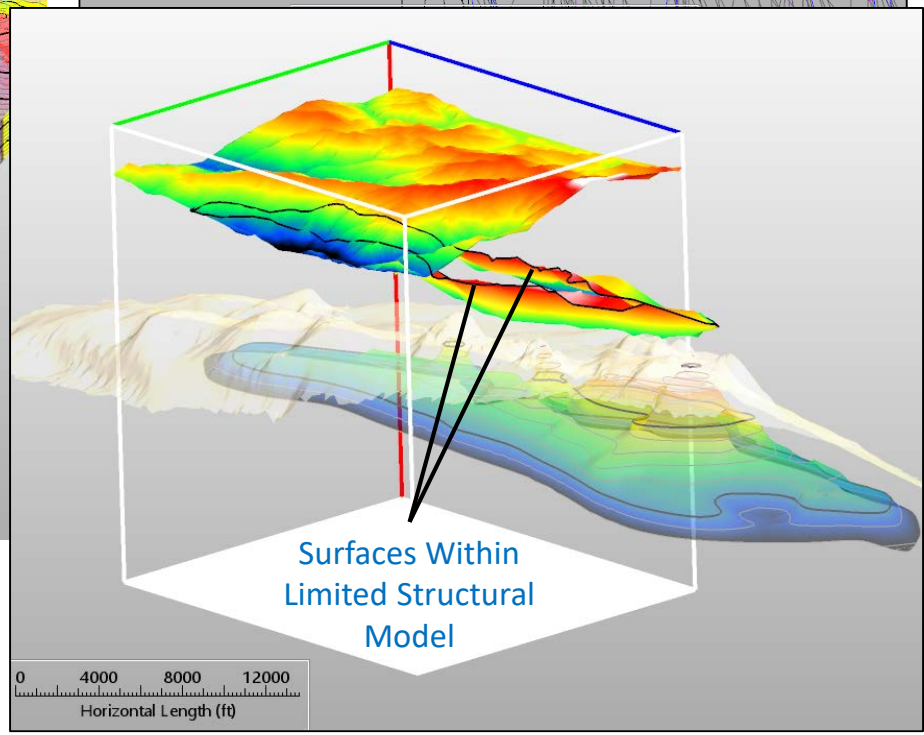
Base Serpentinite Intersection

Top Felsite
Granitic Intrusion

Top Serpentinite
Depth Scaled Colored Surface



Base Serpentinite
Surface Intersection
Points

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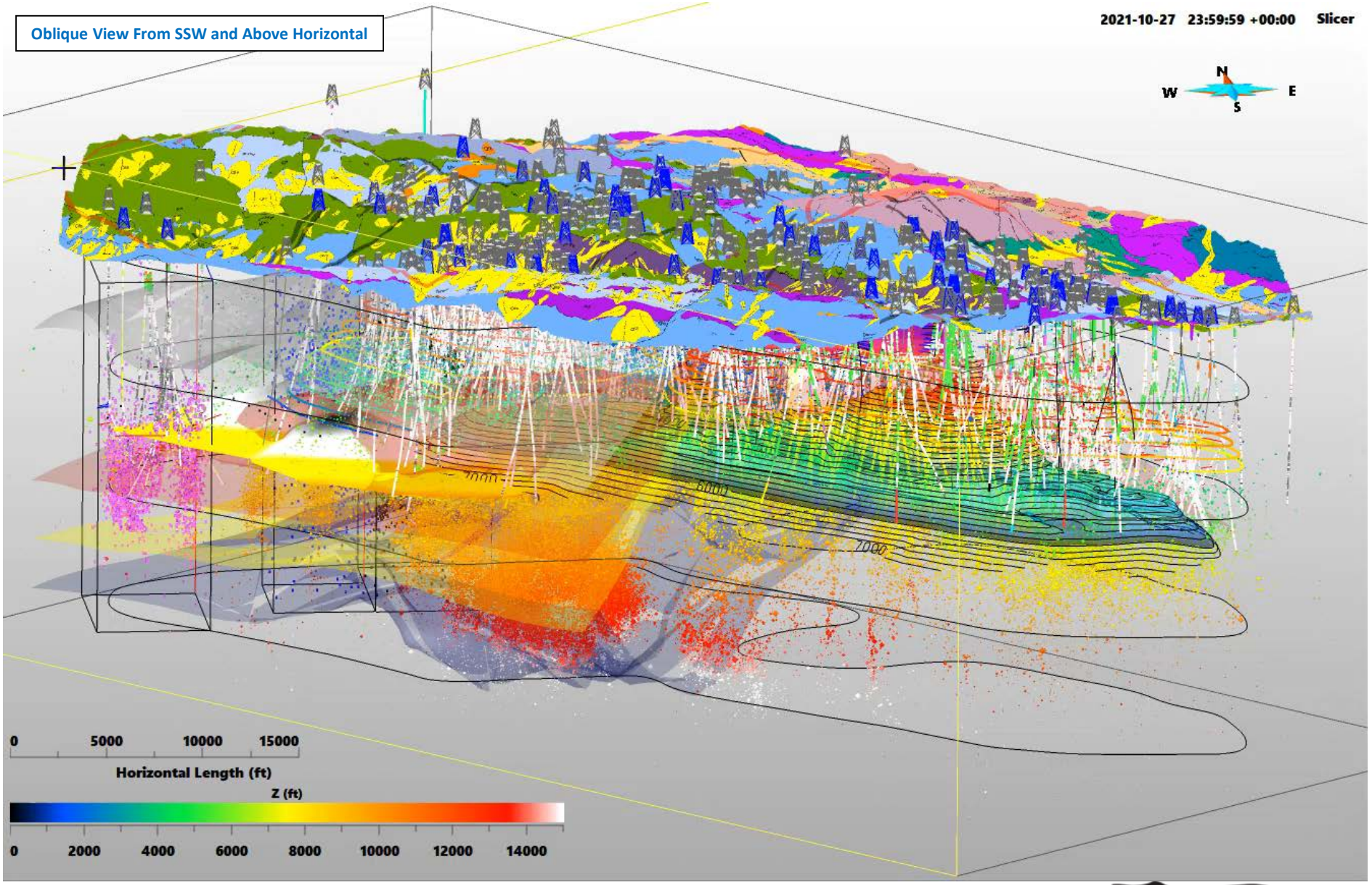
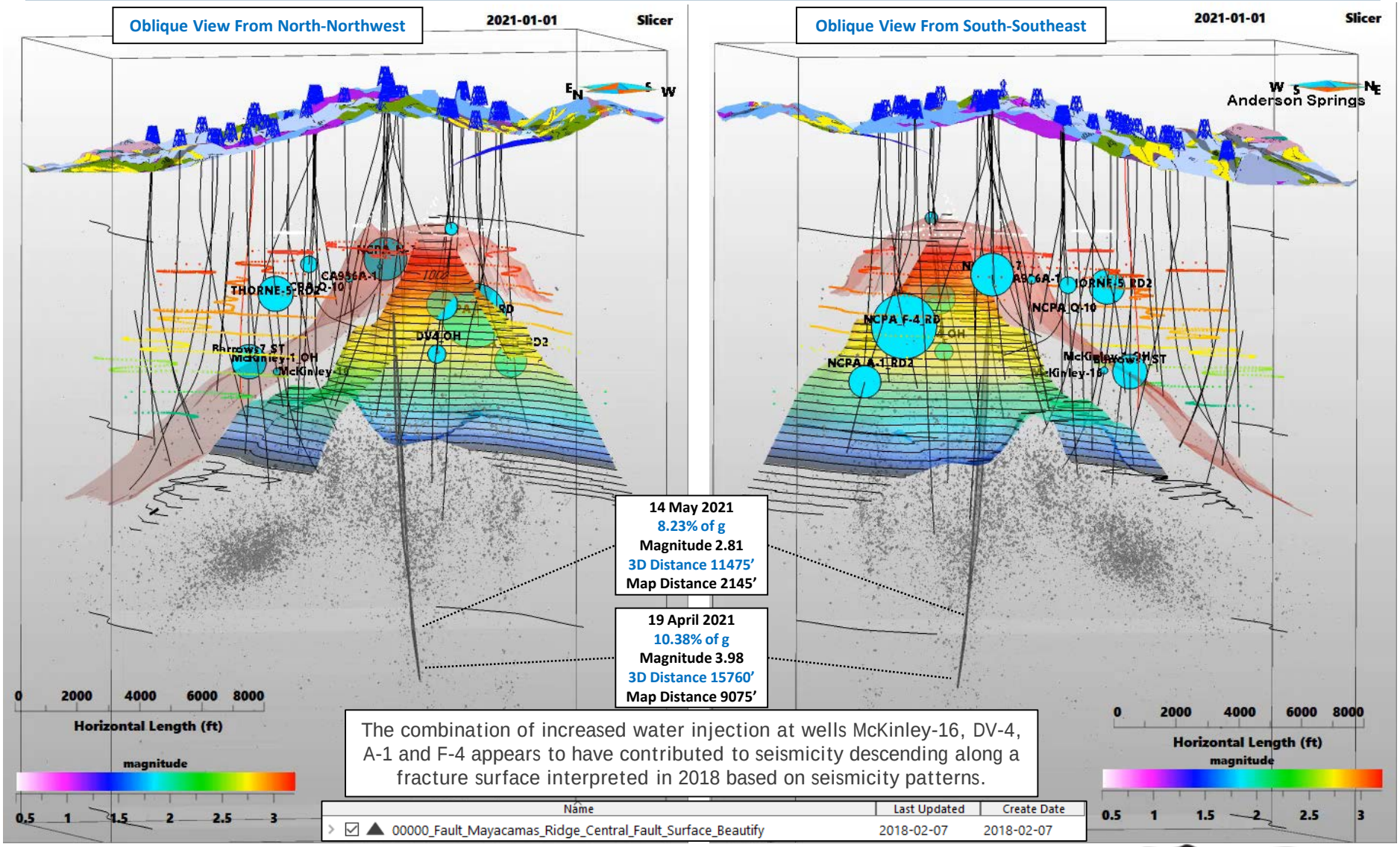
*

**Video**: 3D Structural Model Analysis Example With Volume Slicer

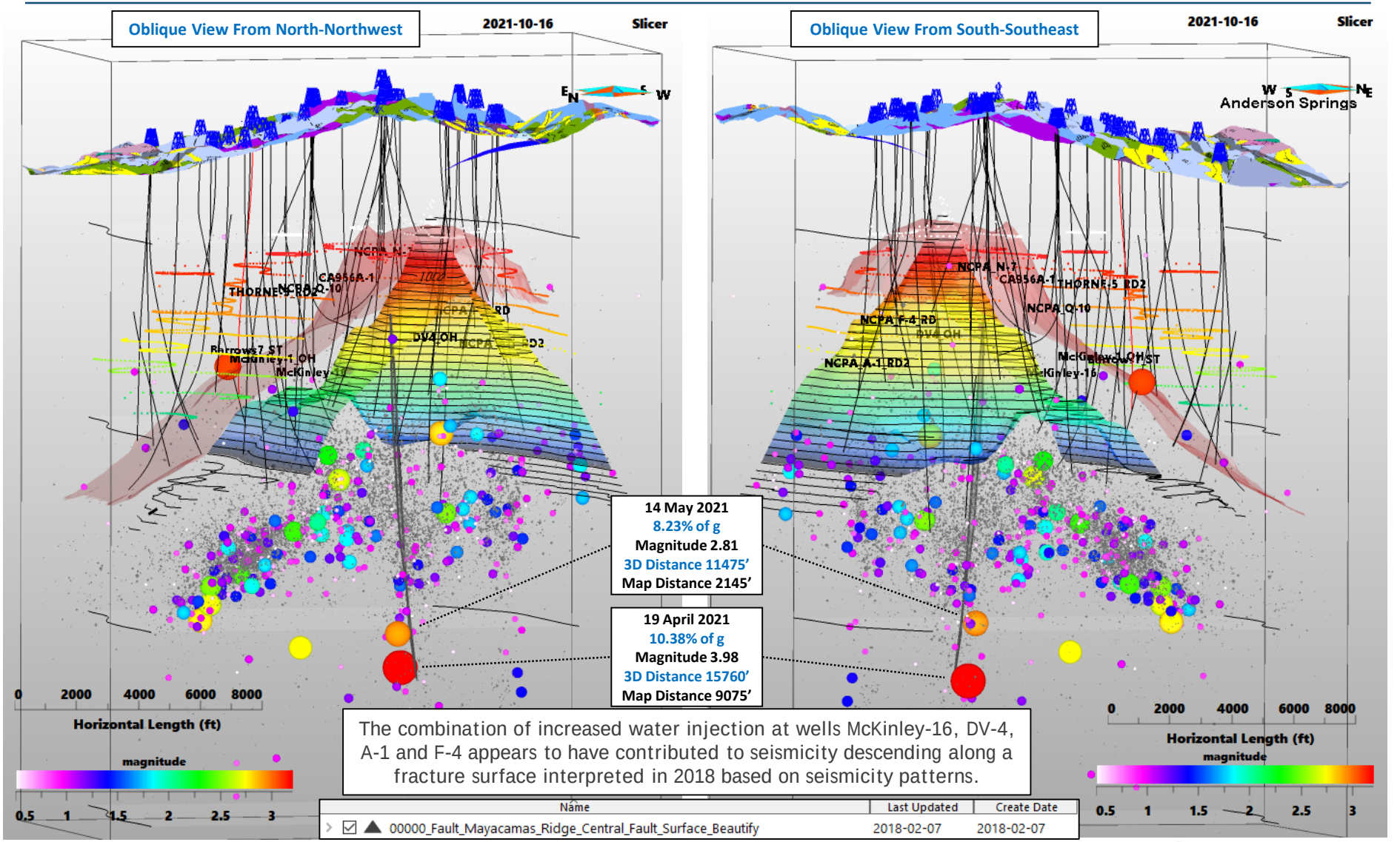


**Videos (Independent Left and Right)**: 3D Structural Model Analysis Example With Volume Slicer
Recent Southeast Geysers Seismicity Related To Fracture Surface Interpreted in 2018 Base On Seismicity Patterns



**Static Images:** 3D Structural Model Analysis Example With Volume Slicer

Recent Southeast Geysers Seismicity Related To Fracture Surface Interpreted in 2018 Base On Seismicity Patterns

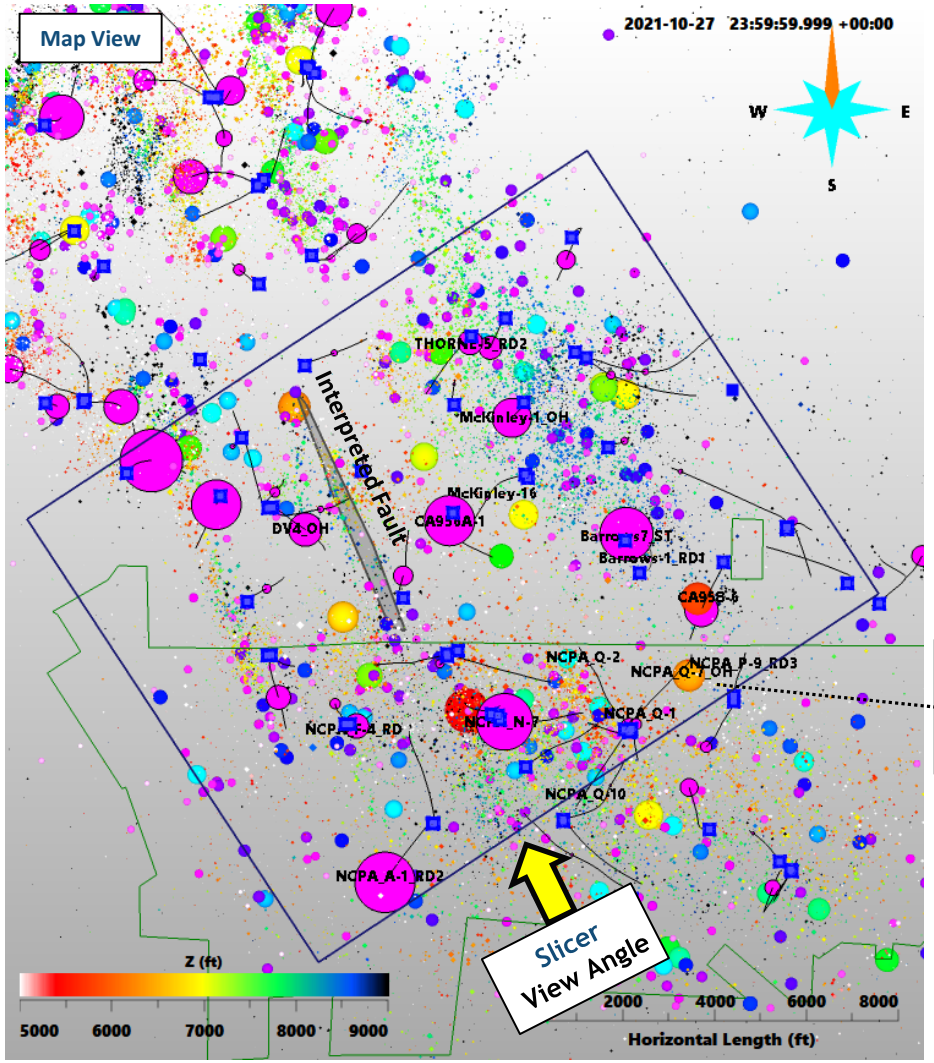


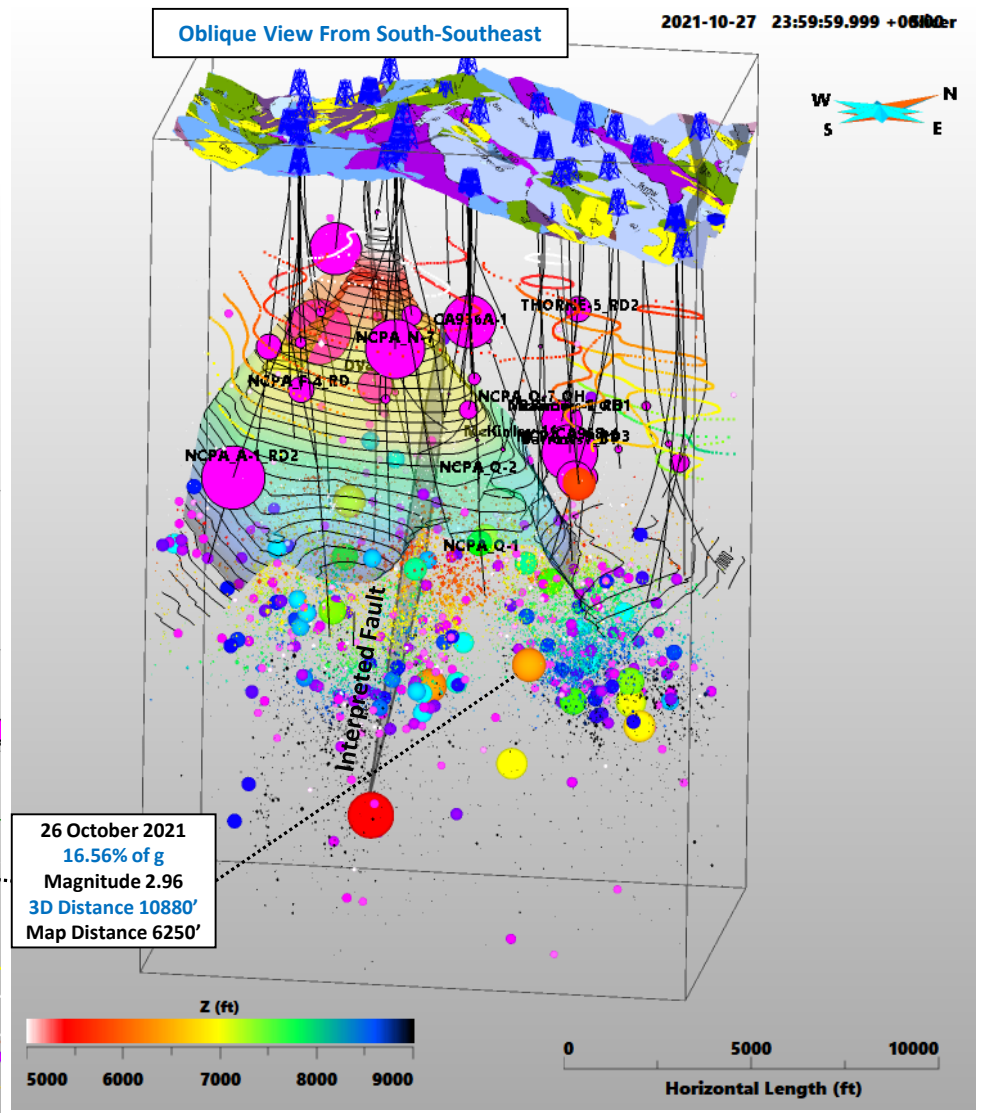
# Seismic Monitoring Advisory Committee Meeting

## 3D Structural Model Slicer View Of 2021.10.26 11:38:51 Magnitude 2.96 Seismic Event

Magnitude 2.96 26 October 2021 Seismic Event
After Reporting Period; Relatively Near Anderson Springs
Peak Ground Acceleration 162.5 cm/sec$^2$ Mercalli Intensity VI*
Event Slightly Within NCPA Lease – However:
Seismicity and Structural Review Suggest That Wells Operated By NCPA and Calpine Likely Contributed To Event.

Purple Disc Radii Scaled To Cumulative Water Injection Volume




* Strong Perceived Shaking, Light Damage Potential



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Magnitude 2.96 26 October 2021 Seismic Event
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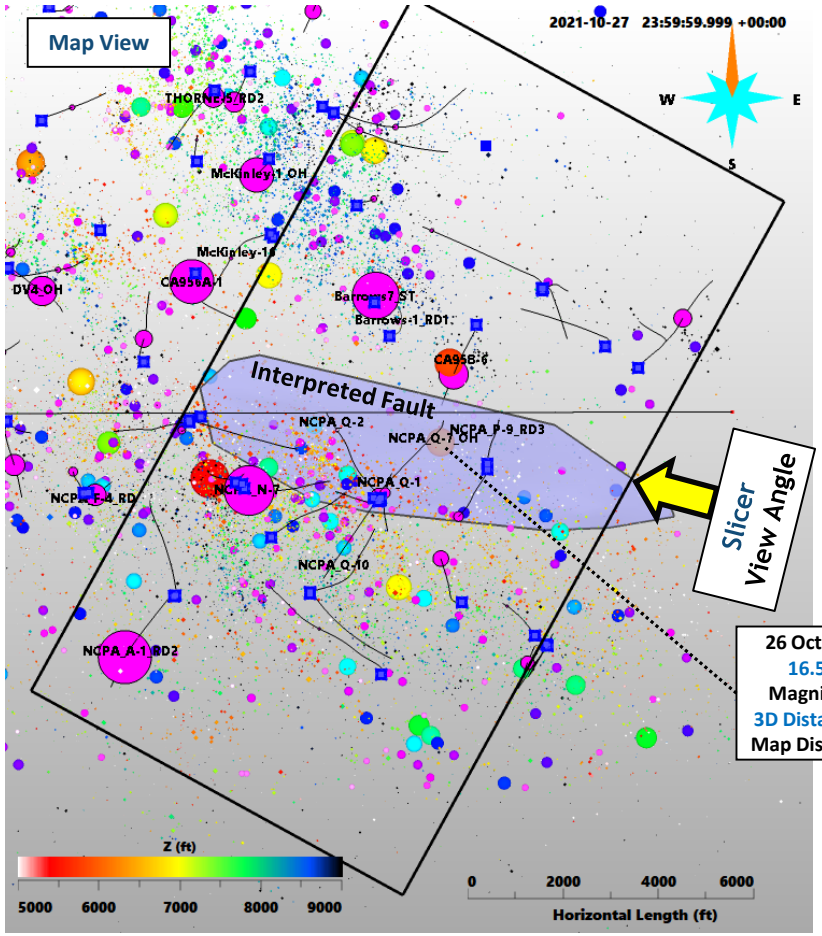
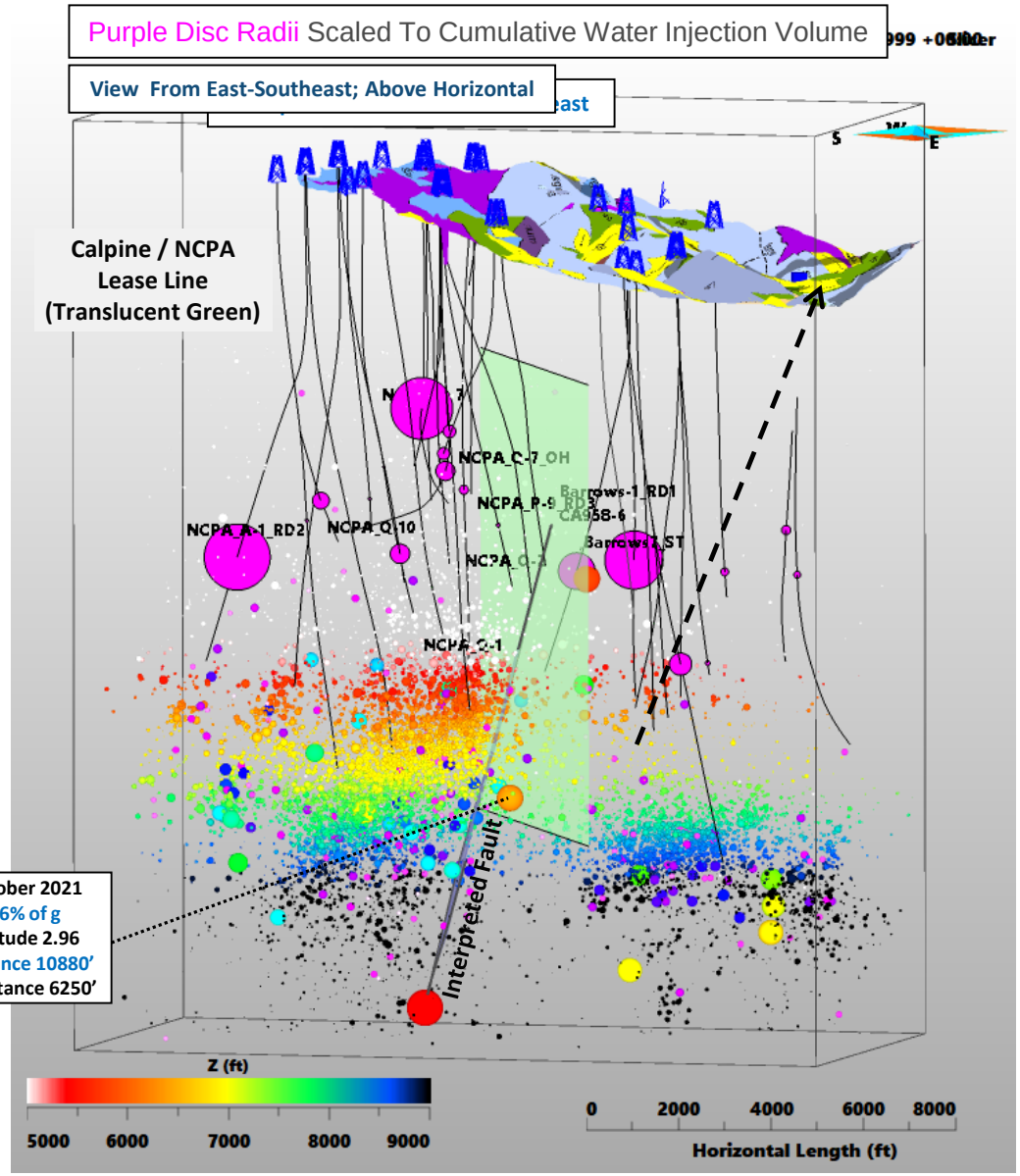


# Geysers Power Company LLC Water Injection Goals

## Improve Injection Distribution

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

## Minimize Injection Rate Variations

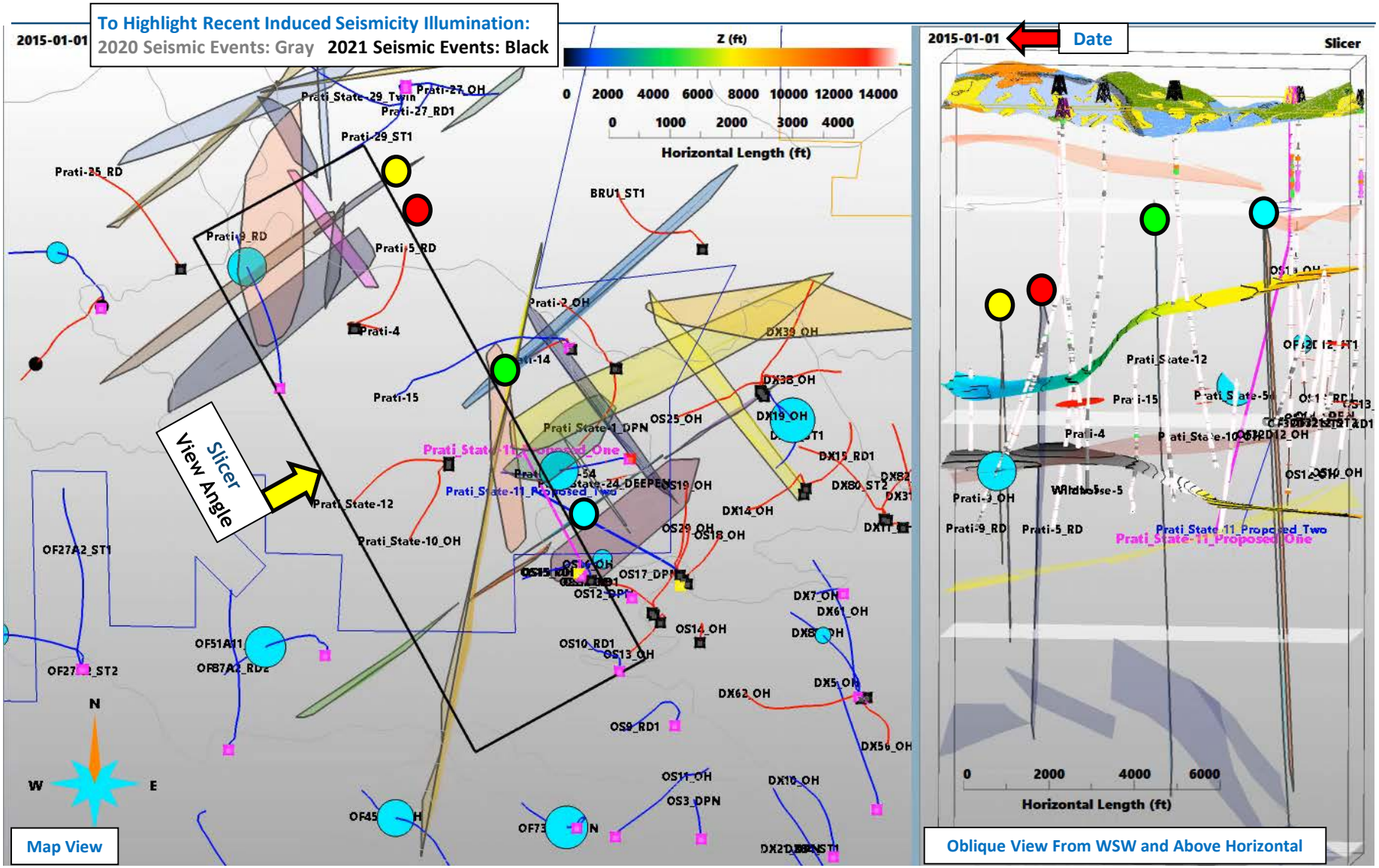
- Individual wells and field-wide
- Emphasis on limited variation for wells nearest communities
- Designed any tests concerning injection rate variability far from communities
- Suitable injection rates per well continually evaluated (dependent on local geology)
- More gradual transition of SRGRP* water for injection
- The City of Santa Rosa assists greatly by providing gradual water supply step-ups and step-downs.

Calpine's goal is a more broadly distributed and uniform "rainfall" of water throughout the reservoir volume for: (1) seismicity mitigation and (2) mass replacement within this renewable resource.

**Thirteen Water Injection Wells Added Since 2017 – Seven New Drilling; Six Conversion-To-Injection**

| Injection Wells Added | Year | Well Name | Measured Depth | Drilling Period | Rig Days |
|---|---|---|---|---|---|
| **New Drilling (7)** | 2017 | CMHC-8 | 9112' | 28 February 2017 to 10 May 2017 | 71 |
| | 2018 | GDC-34 | 6827' | 16 August 2018 to 15 October 2018 | 60 |
| | 2019 | Prati-15 | 11018' | 18 May 2019 to 27 July 2019 | 70 |
| | 2020 | GDC53B-13 | 5500' | 22 May 2020 to 27 June 2020 | 36 |
| | 2020 | LF-51 | 9908' | 24 July 2020 to 08 October 2020 | 76 |
| | 2020 | Thorne-11 | 8919' | 12 November 2020 to 22 January 2021 | 71 |
| | 2021 | Beigel-4 | 8089' | 13 February 2021 to 09 April 2021 | 55 |
| | | | | | |
| | | | | Conversion Date | |
| **Conversion-To_Injection (6)** | 2017 | OS-15 | 9387' | 12 January 2017 | |
| | 2017 | DX-46 | 8562' | 19 February 2017 | |
| | 2019 | CA74F-21 | 12900' | 13 November 2019 | |
| | 2019 | CA87E-21 | 8772' | 13 September 2020 | |
| | 2020 | DX-21 | 10045' | 19 July 2020 | |
| | 2020 | Prati-27 (RD1) | 9000' | 09 October 2020 | |

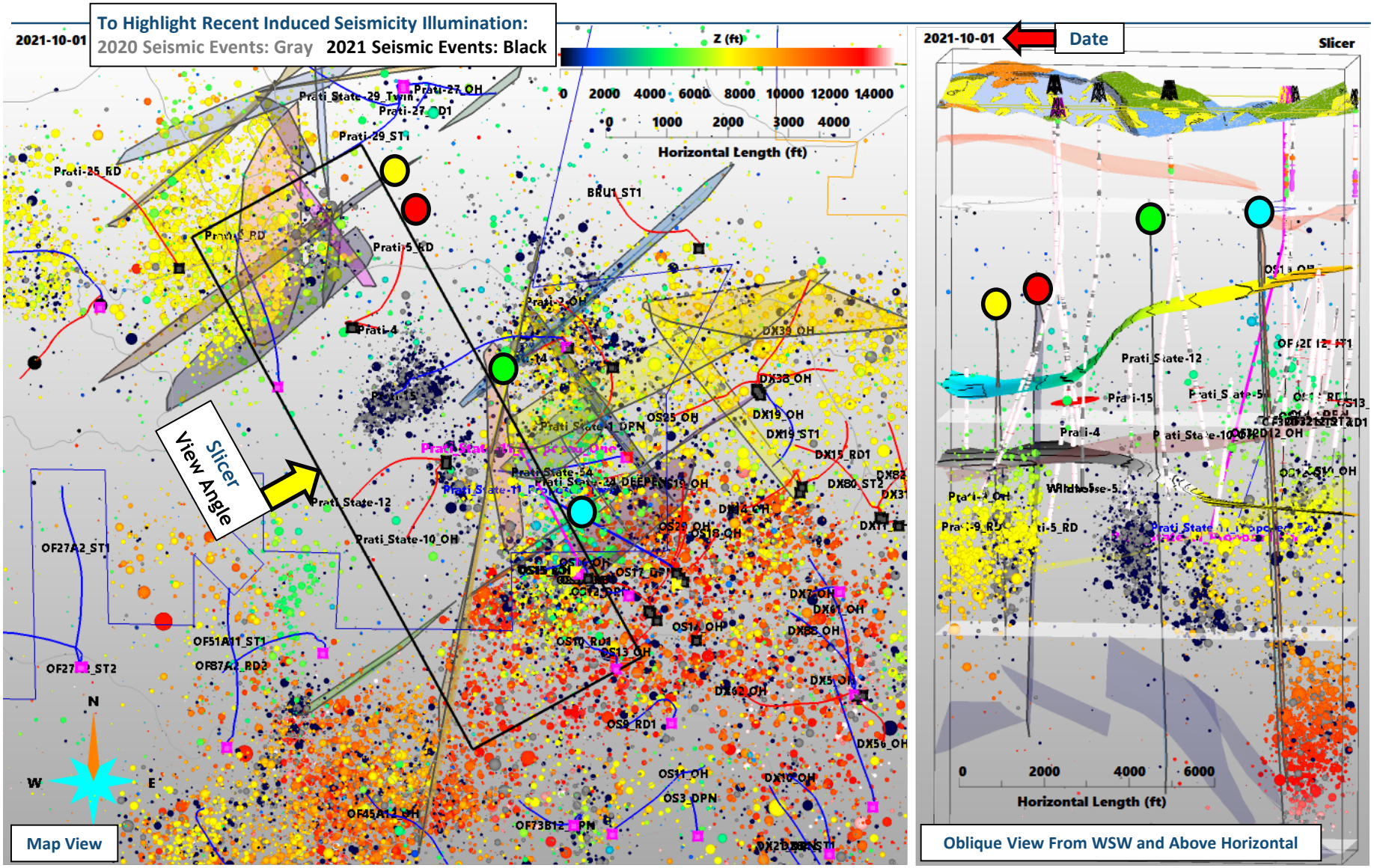
**Video**: Induced Seismicity Animation From January 2015 to October 2021 At Three-Month Interval
Selected Northwest Geysers Faults Emphasize Steam Reservoir Compartmentalization



# Seismic Monitoring Advisory Committee Meeting

## Induced Seismicity From January 2015 to October 2021 At Three-Month Interval

## Selected Northwest Geysers Faults Emphasize Steam Reservoir Compartmentalization



# Seismic Monitoring Advisory Committee Meeting

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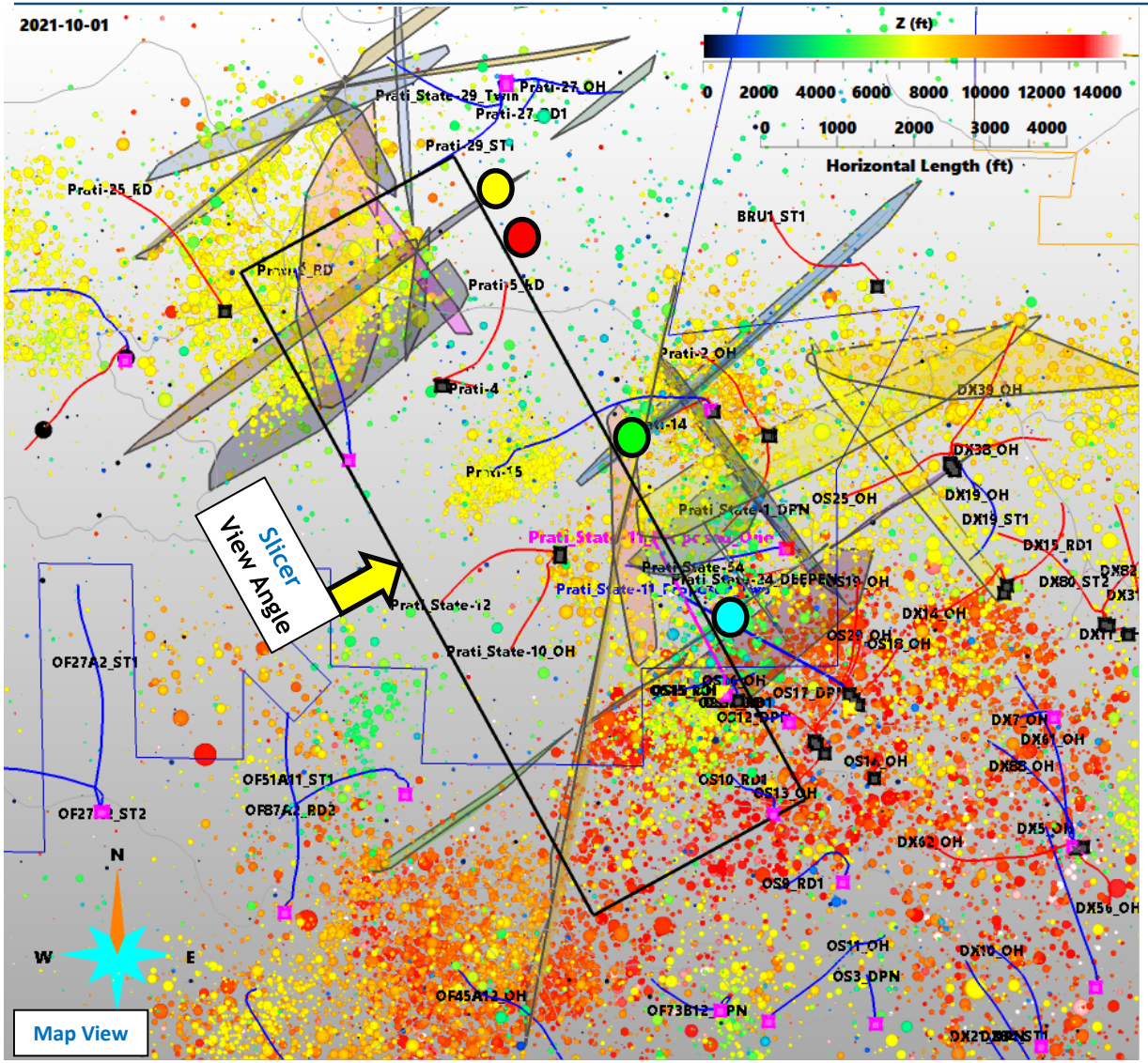
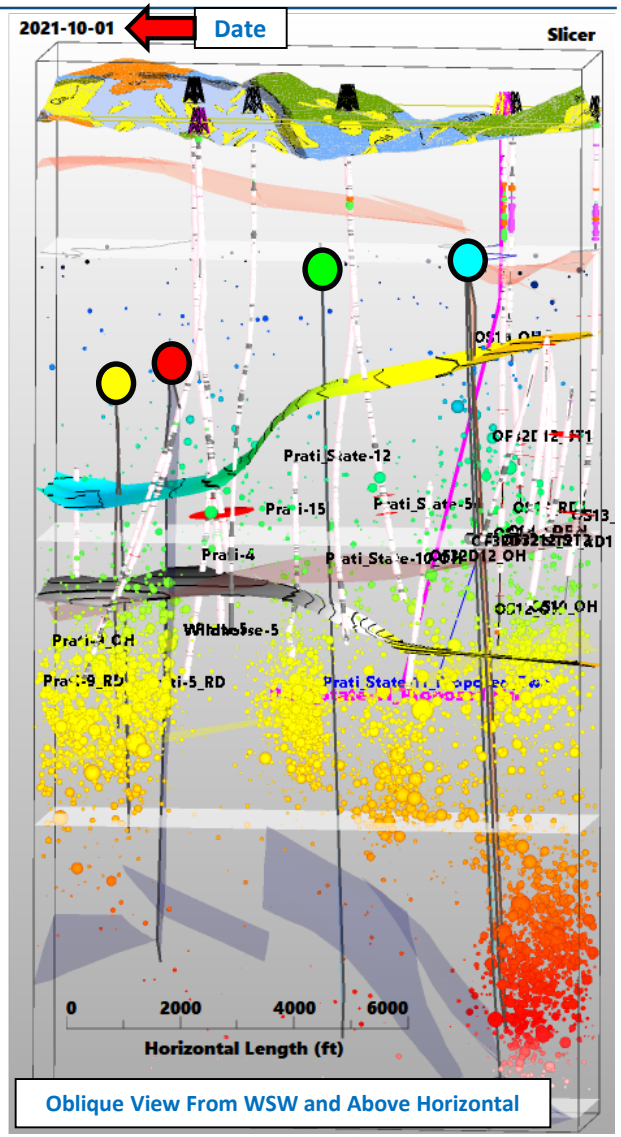


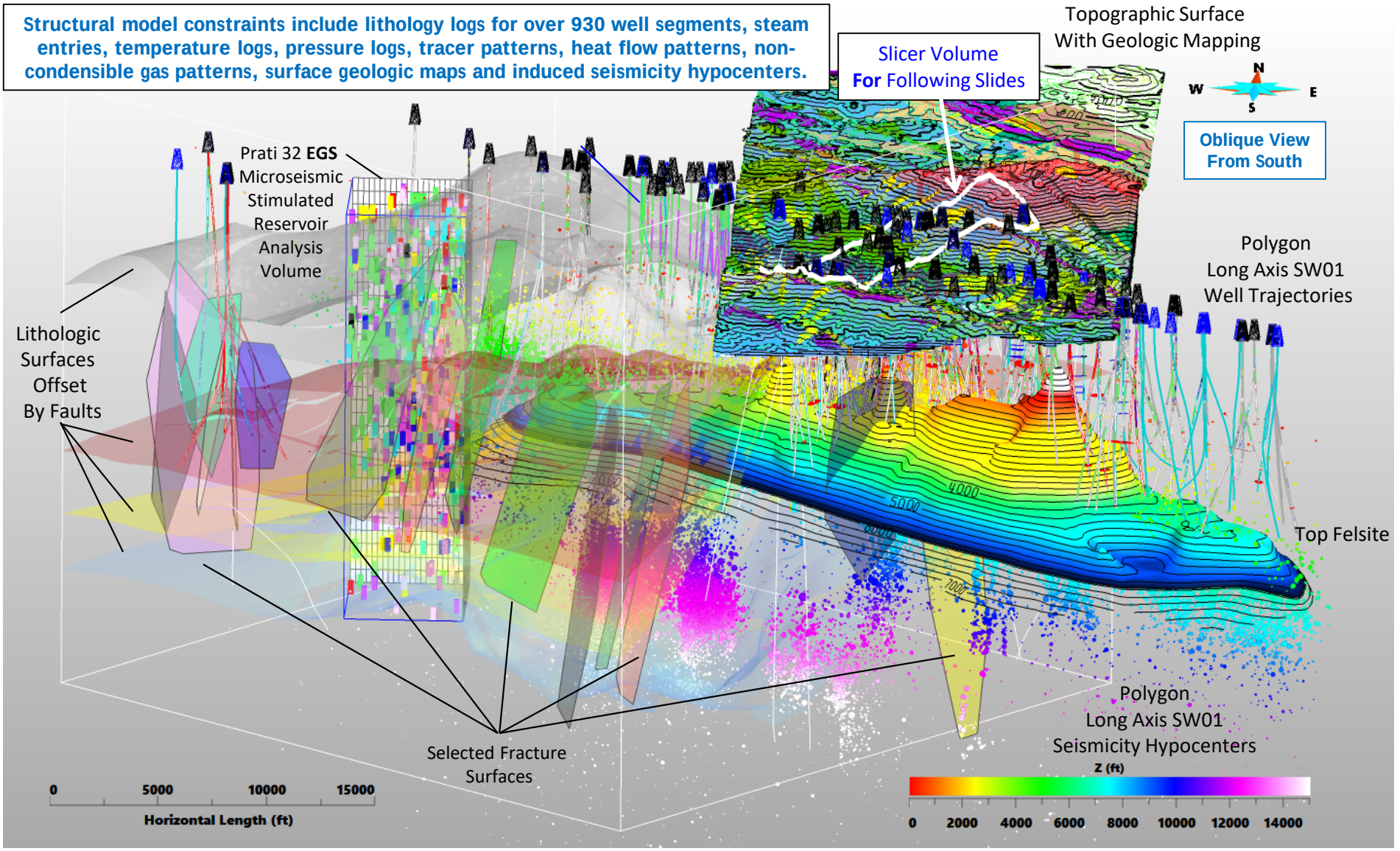

CALPINE®


THE GEYSERS
GEYSERS POWER COMPANY, LLC
www.geysers.com

# Calpine 3D Structural Model (SKUA GOCAD Software*)

**A refined understanding of The Geysers' fluid flow paths, fluid boundaries, reservoir heterogeneity and reservoir compartmentalization *assists* with well planning / targeting, real-time drilling analysis, reservoir management and provides the potential for improved seismicity mitigation at The Geysers.**

**Structural model constraints include lithology logs for over 930 well segments, steam entries, temperature logs, pressure logs, tracer patterns, heat flow patterns, non-condensible gas patterns, surface geologic maps and induced seismicity hypocenters.**



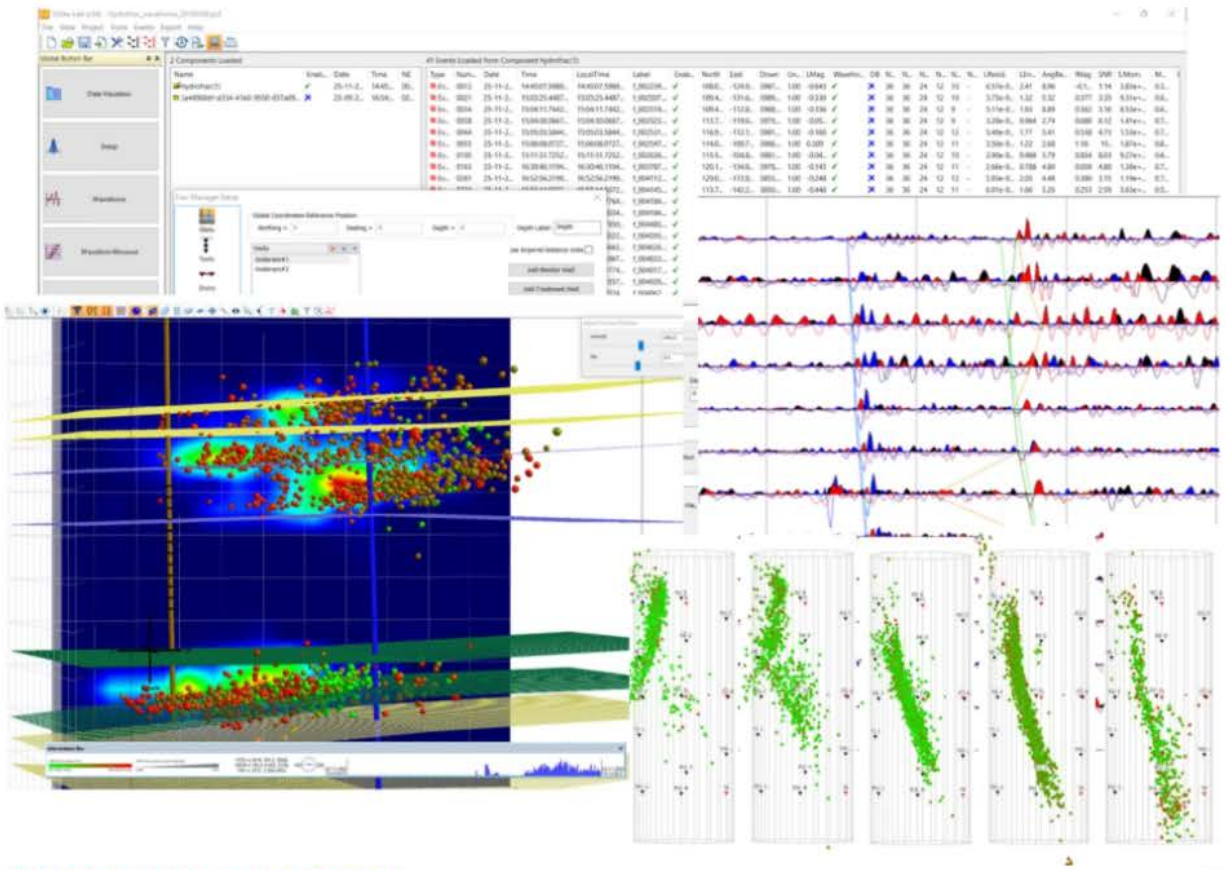

* Subsurface Knowledge Unified Approach  Geologic Object Computer Assisted Design

Geysers Power Company, LLC has conducted on-site testing of this well-developed software to assist with detailed seismicity analysis at The Geysers and is currently arranging for an early 2022 software purchase.

## *InSite Seismic Processor*

ITASCA

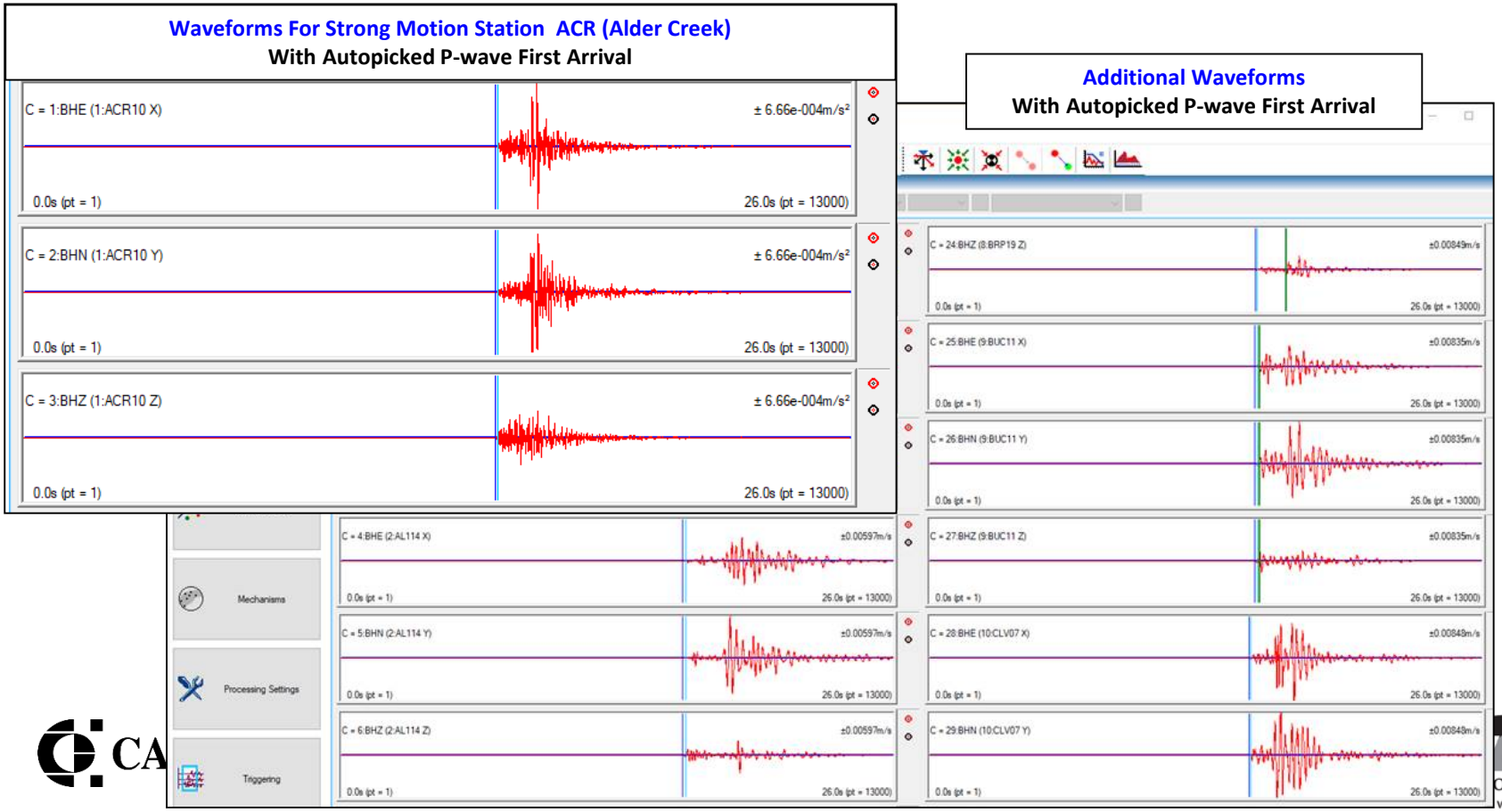
- Itasca's seismic software integrating data management, processing, analysis and interpretation
- Developed over the past 20 years incorporating tools from internal R&D and collaboration projects with clients and partners
- Used at all scales of seismic and acoustic monitoring, from laboratory rock deformation tests to processing of local and regional seismicity
- Latest version 3.16.1 released March 2020



# Applied Seismology / Itasca InSite-Geo Software Testing

Seismic events exceeding threshold criteria were isolated from The Geysers continuous waveform data and processed within the Applied Seismology / Itasca InSite-Geo software. Waveforms for the East-West, North-South and Vertically oriented sensors are shown for a 12 August 2020 magnitude 3.9 seismic event processed on a Geysers Power Company, LLC workstation.

Larger seismic events typically have usable waveforms (with signal well above the noise floor) for the majority of the 38 three-component LBNL / Calpine seismic stations.



# Santa Rosa Geysers Recharge Project Water Volume 01 April 2021 Through 30 September 2021