



America's Premier Competitive Power Company
... Creating Power for a Sustainable Future



Seismic Monitoring Advisory Committee Meeting

01 October 2020 to 31 March 2021 Reporting Period

Virtual Meeting Due to COVID-19 Concerns

10 May 2021

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**
- **Water Injection and Induced Seismicity Animations ***
- **Calpine 3D Structural Model**
 - 3D Pre-Drilling Project Analysis (Well Planning)
 - Fracture / Fault Analysis
 - Local Seismicity Analysis
- **Strong Motion Data Analysis**
 - Peak Ground Acceleration
 - Energy / Distance / Modified Mercalli Intensity
- **Community Hotline**
- **Seismic Events Occurring Near Anderson Springs After Reporting Period**
- **Summary**

* All Presentation Seismicity Analysis Animations Disabled To Minimize Virtual Meeting Data Transfer Issues

Seismic Monitoring Advisory Committee Meeting

Geysers Geothermal Field, Nearby Communities and Seismic Monitoring Networks

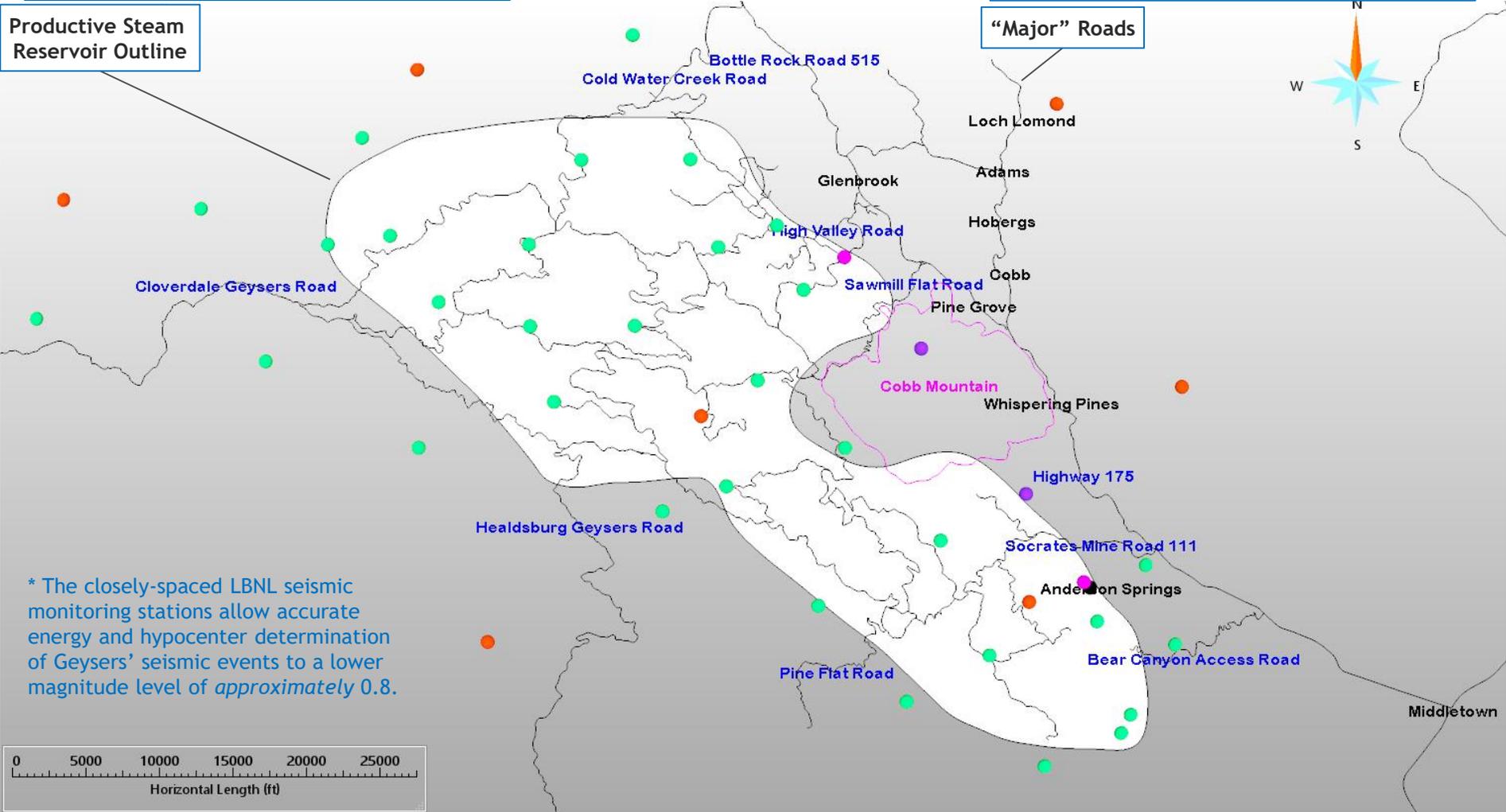
● **Lawrence Berkeley National Laboratory**
 2003 installation; continuing upgrades
 34 stations
 Magnitude 0.8 Threshold *
 Primary Contacts: Dr. Seiji Nakagawa
 Dr. Ernie Majer

Strong Motion Accelerometers
● 2017/18 Nanometrics installation (2)
● 2020 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

Productive Steam Reservoir Outline

"Major" Roads



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



Seismic Monitoring Advisory Committee Meeting

Improvements To LBNL / Geysers Power Company Seismic Monitoring Network

Geysers Power Company Has Recently Purchased Equipment Integrated Into Seismic Monitoring Network To Improve Reliability. This Equipment Is Installed by GPC-Contracted Seismic Expert Ramsey Haught, **Including:**

24 Geospace Three-Component 2 Hz Sensors
Replacement Of Sensors With Component Failure
\$2,900 per station installed

4 Nanometrics Titan Accelerometer Stations
Recording Peak Ground Acceleration Along
Eastern Perimeter Of Geysers Geothermal Field
\$7,300 per station installed

3 Intuicom Radio Pairs
Improving Seismic Data Transmission Pathways
Previously Band-Limited With Some Data Loss

30 Sunlyte/MK Deep Cycle Batteries
36 Purchased - Two Per Station

10 Taurus Digitizers
Purchased LBNL / Installed Geysers Power Company
Outdated / Incompatible Equipment Replaced



Radio Antennae

Hummingbird West (HBW)
LBNL Seismic Station
Northwest Geysers



Solar Panel



Two Batteries
GPS Unit (Timing)
Radio Transmitter
Digitizer



Three-Component
Seismic Sensor
(Below Surface)



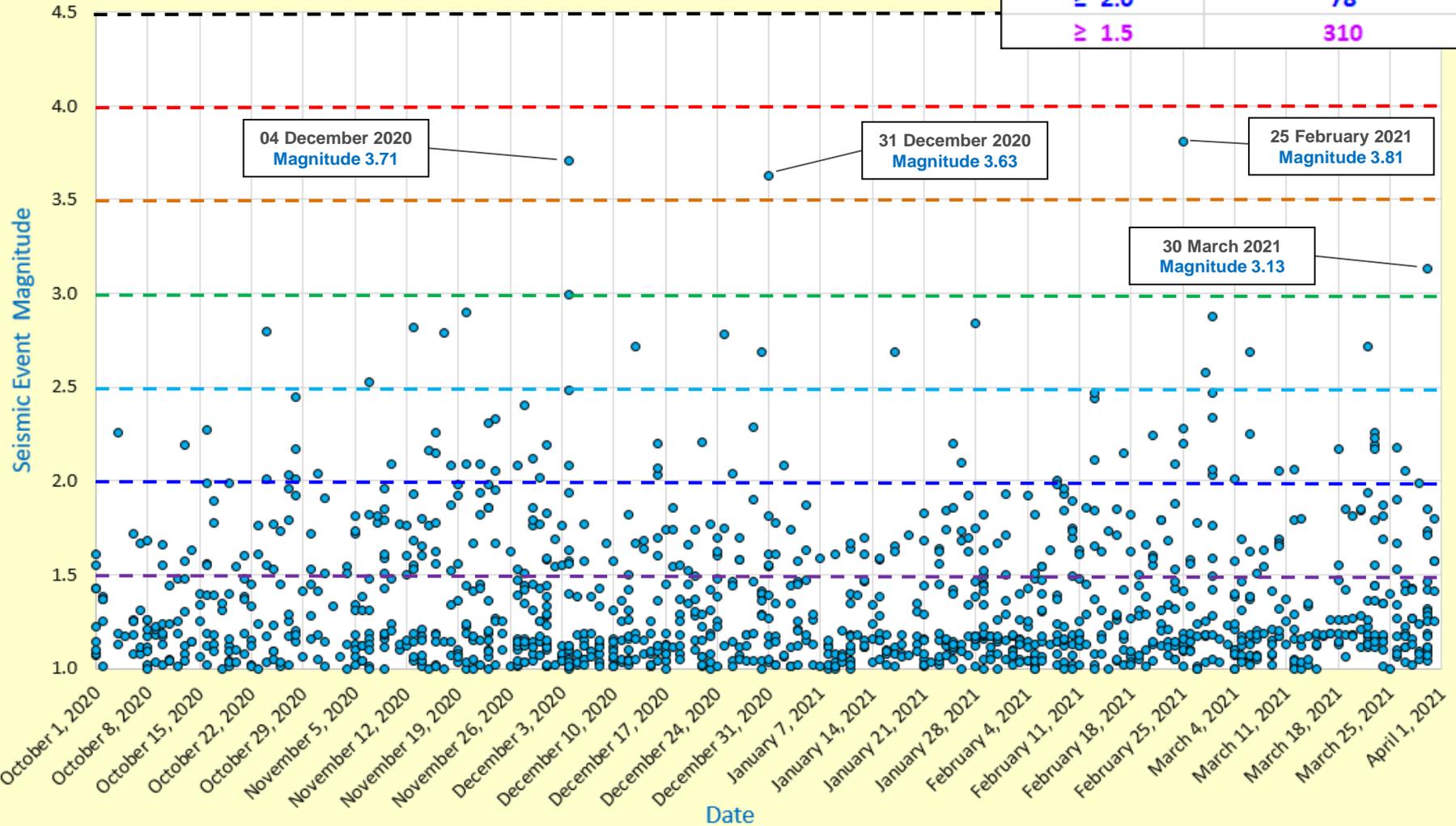
Seismic Monitoring Advisory Committee Meeting

Field-wide Seismicity Analysis

01 October 2020 to 31 March 2021

Magnitude	Number of Events
≥ 4.5	0
≥ 4.0	0
≥ 3.5	3
≥ 3.0	4
≥ 2.5	19
≥ 2.0	78
≥ 1.5	310

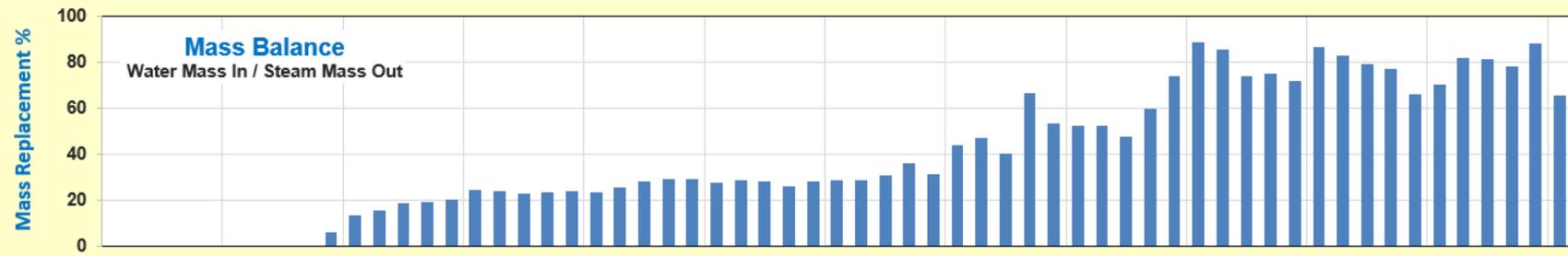
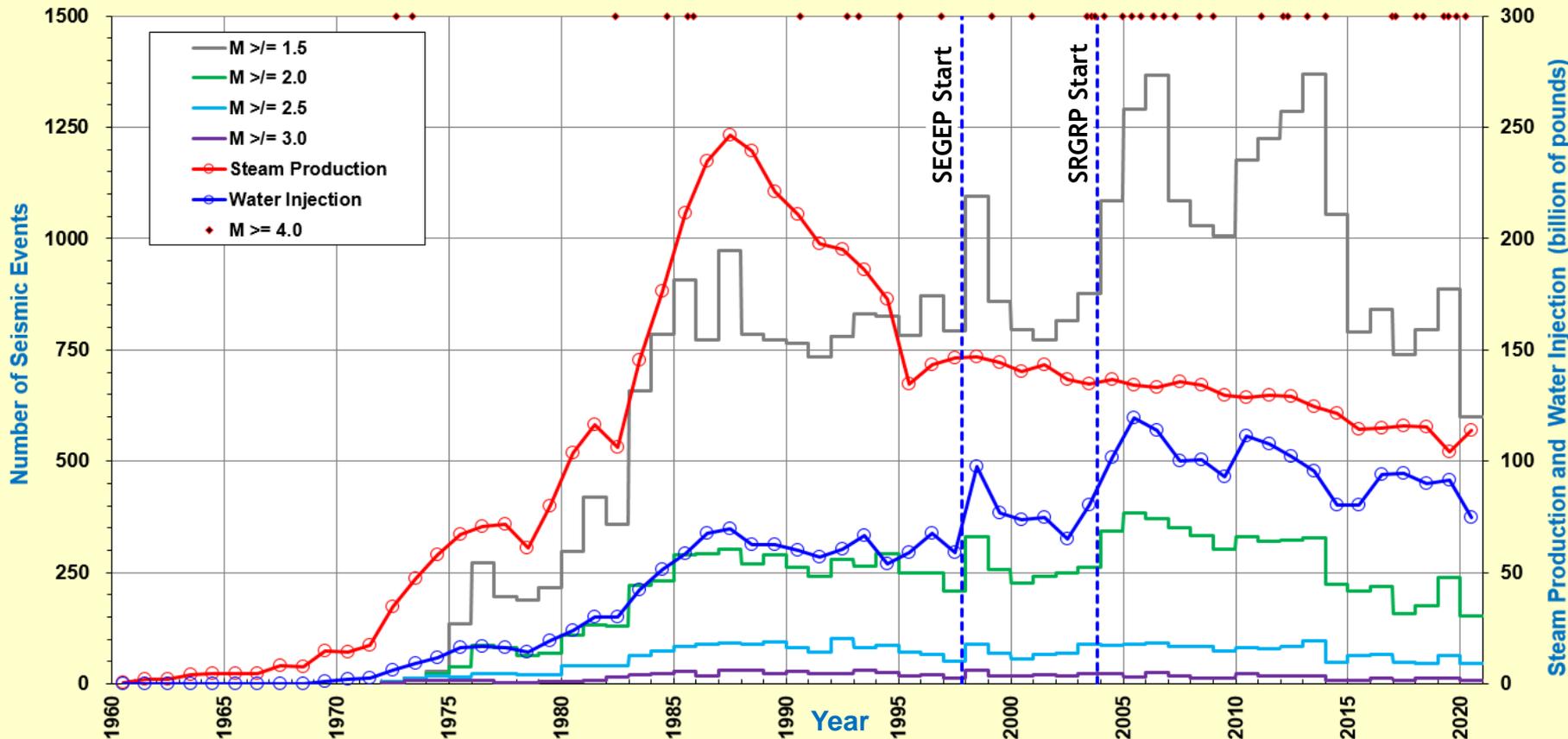
The Geysers Fieldwide Seismicity
01 October 2020 to 31 March 2021



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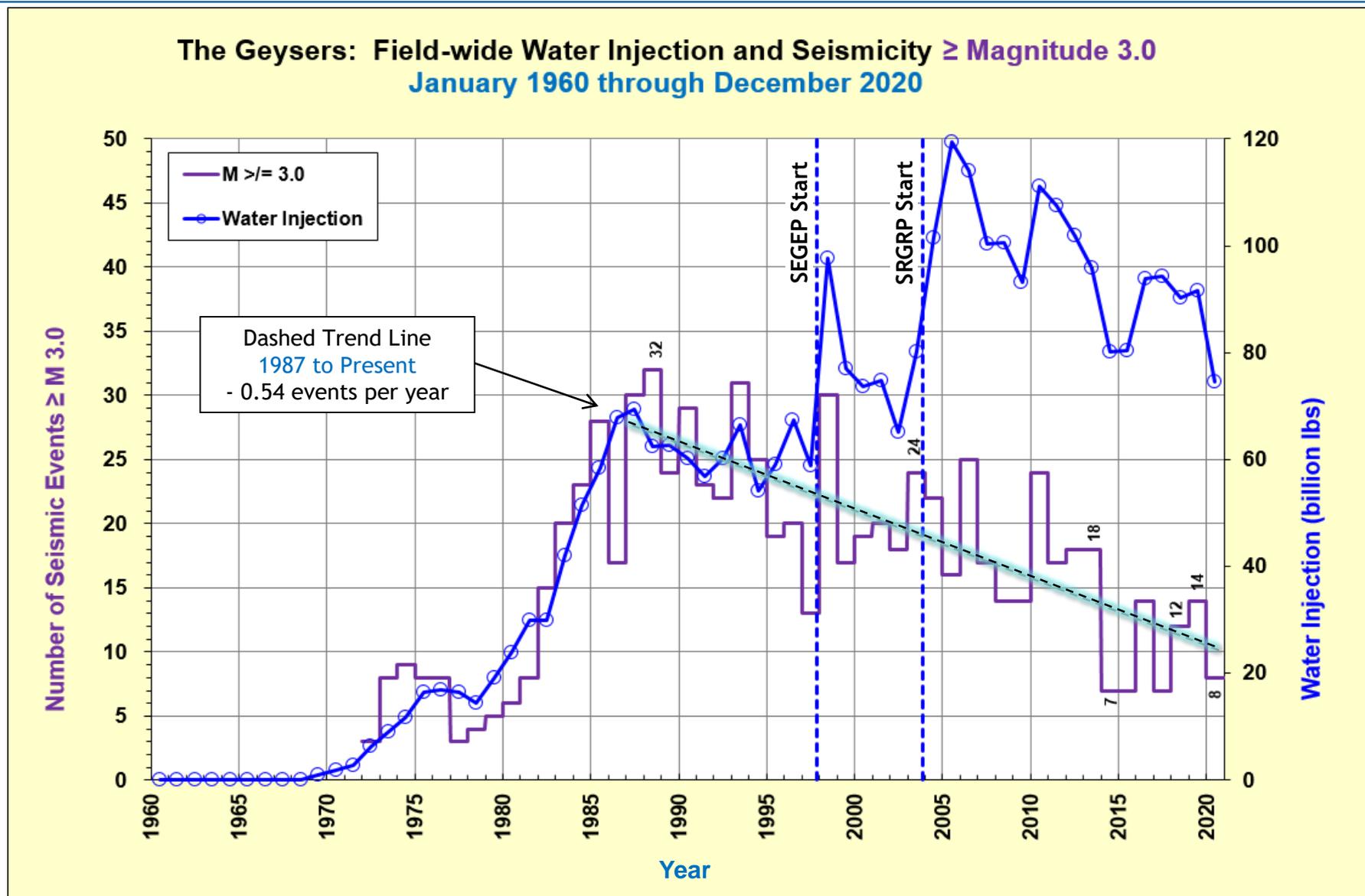
Yearly Field-wide Steam Production, Water Injection and Seismicity

The Geysers: Field-wide Steam Production, Water Injection and Seismicity
January 1960 through December 2020



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

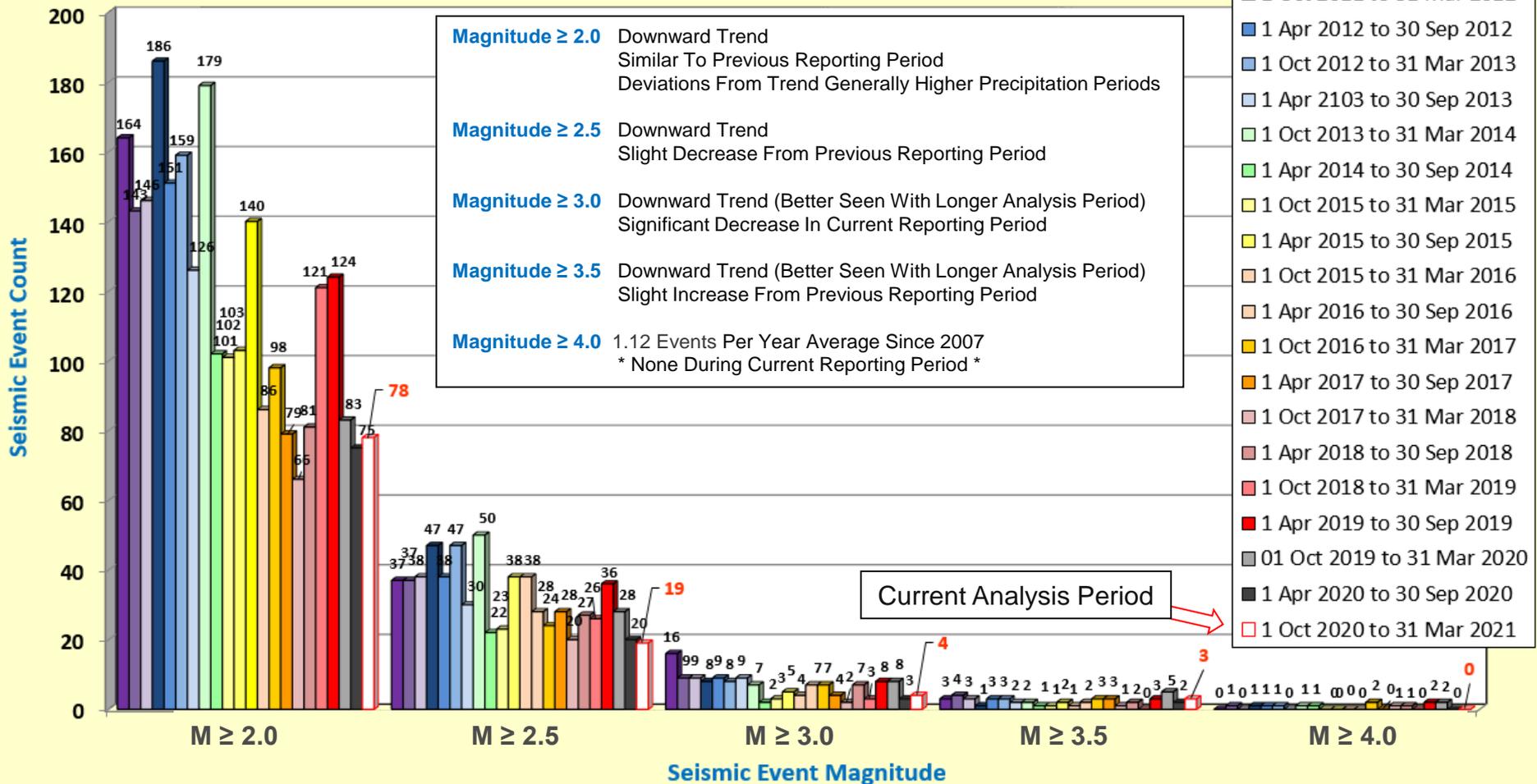


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Fieldwide Seismicity Analysis

Comparison of Twenty-Two Semi-Annual Reporting Periods Since 01 April 2010

Field-wide Seismicity Analysis Events ≥ Specified Magnitude Twenty-Two Semi-Annual Periods Since 01 April 2010



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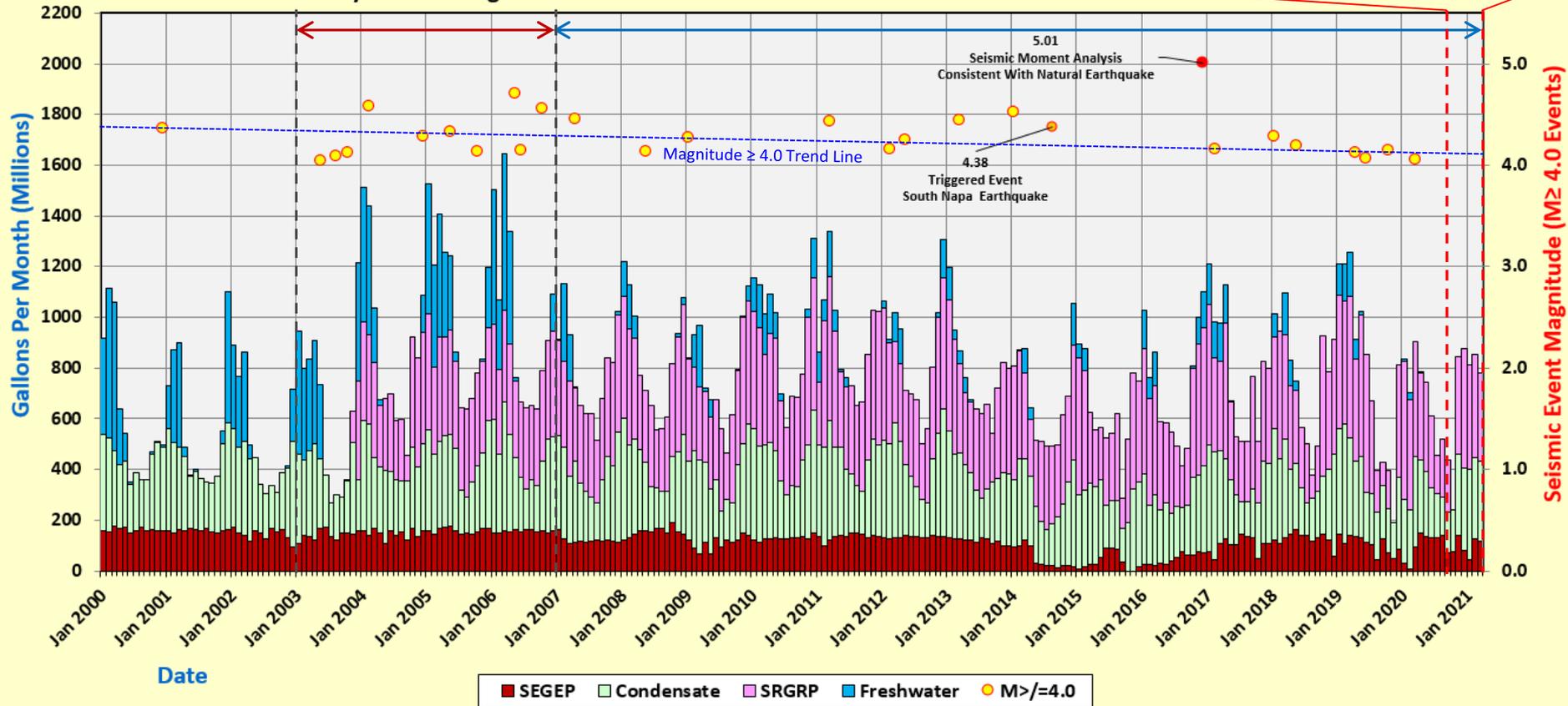
Monthly Field-wide Water Injection By Water Source And Magnitude ≥ 4.0 Seismicity

Average Number of Magnitude ≥ 4.0 Events Since January 2007 is 1.12 Per Year

Time Period	Magnitude ≥ 4.0 Seismic Events
January 2003 through December 2006	2.50 per year
January 2007 through March 2021	1.12 per year

Water Supply for Reporting Period (Six Months)				
Water Injection Sources (Gallons)				
Month	SEGRP	SRGRP	Condensate	Fresh Water
October	76,232,000	0	164,268,340	0
November	140,244,000	384,280,000	320,659,640	0
December	81,854,000	469,110,000	325,125,768	0
January	45,943,000	414,830,000	353,767,398	0
February	124,948,000	404,050,000	323,624,586	0
March	116,859,000	350,580,000	314,626,928	0

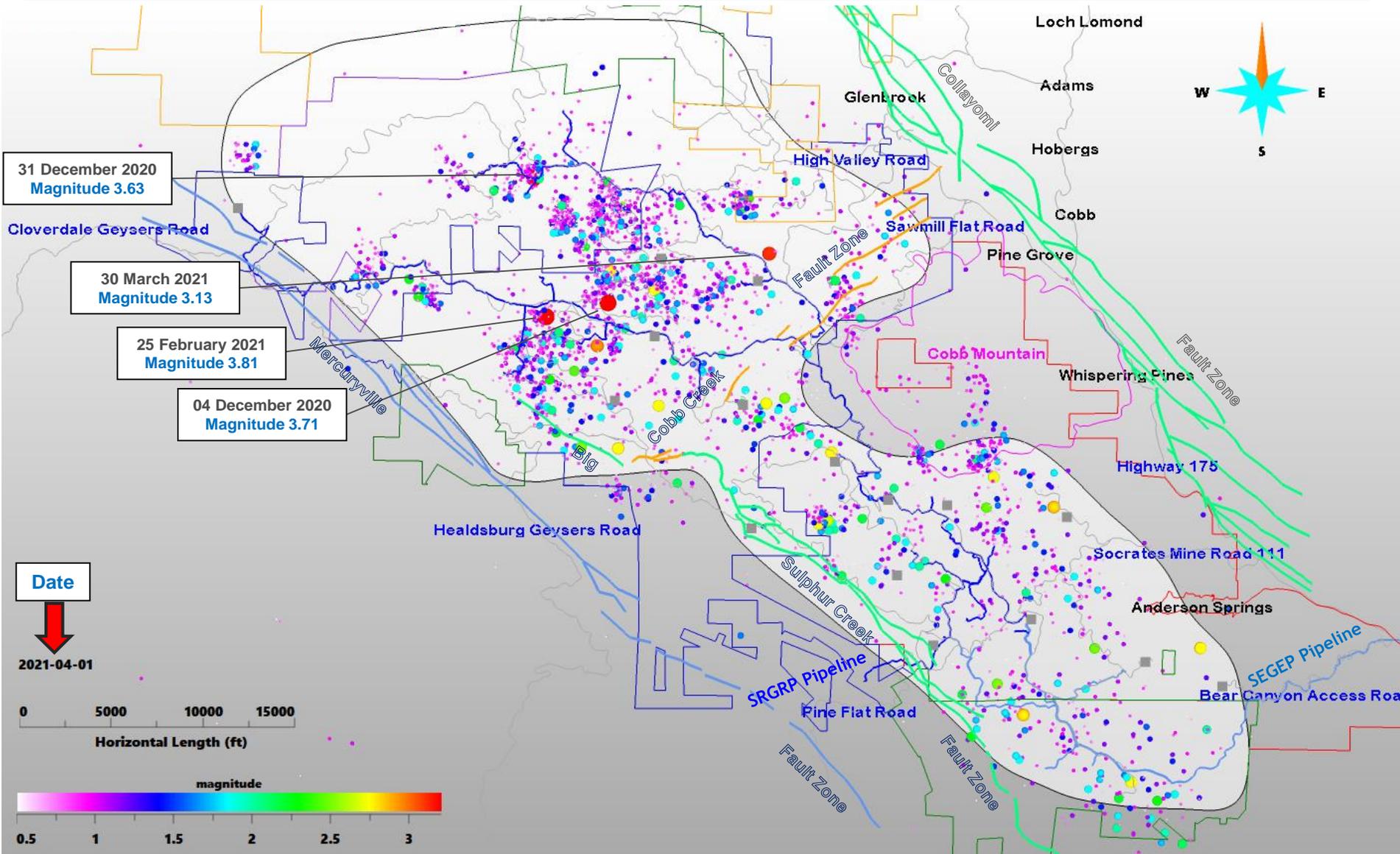
The Geysers
Calpine Fieldwide Water Injection Sources
Magnitude ≥ 4.0 Seismicity
01 January 2000 through 31 March 2021



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Field-wide Seismicity Animation At Two Week Interval

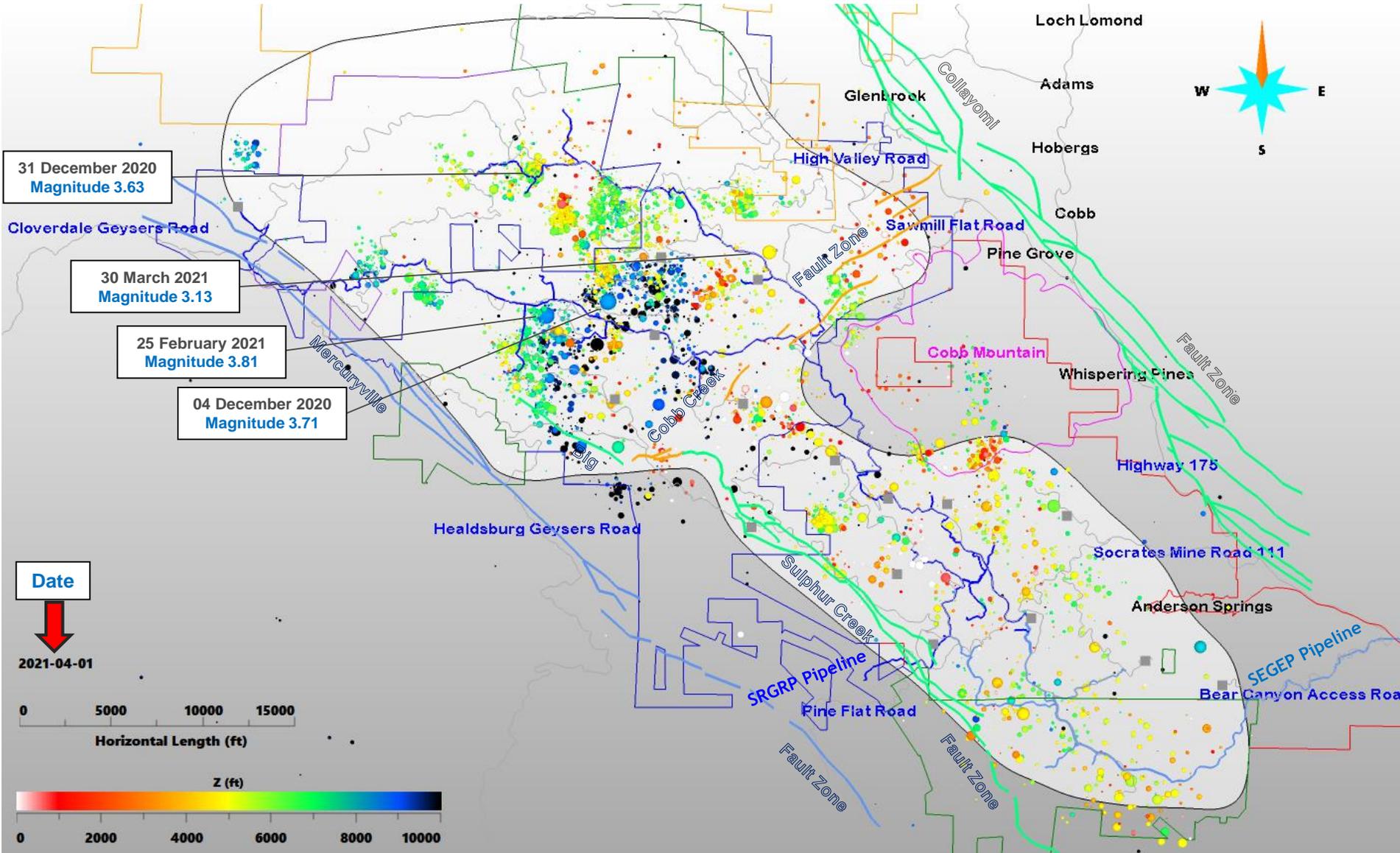
Seismic Events Color Scaled By Magnitude



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Field-wide Seismicity Animation At Two Week Interval

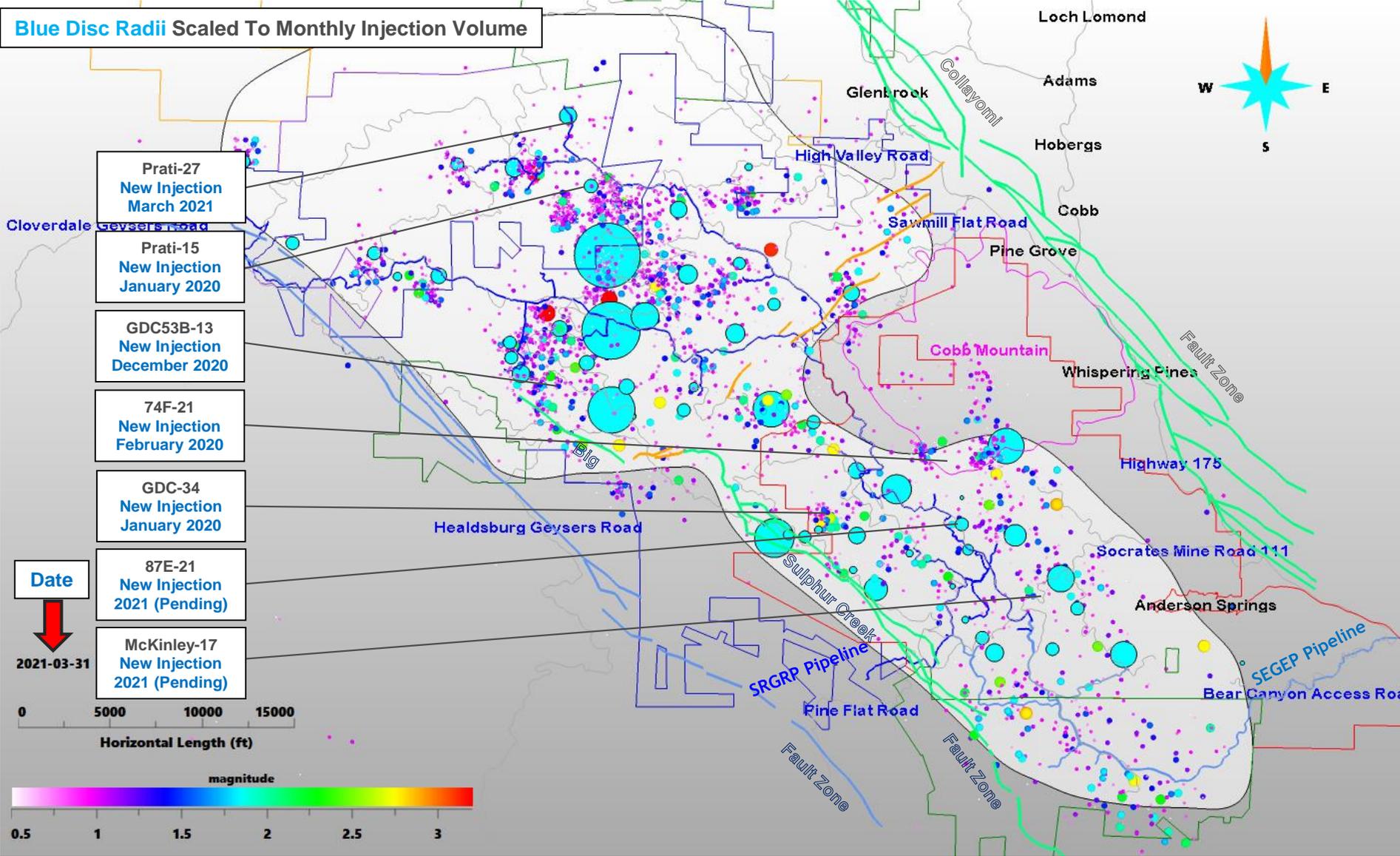
Seismic Events Color Scaled By Subsea Depth



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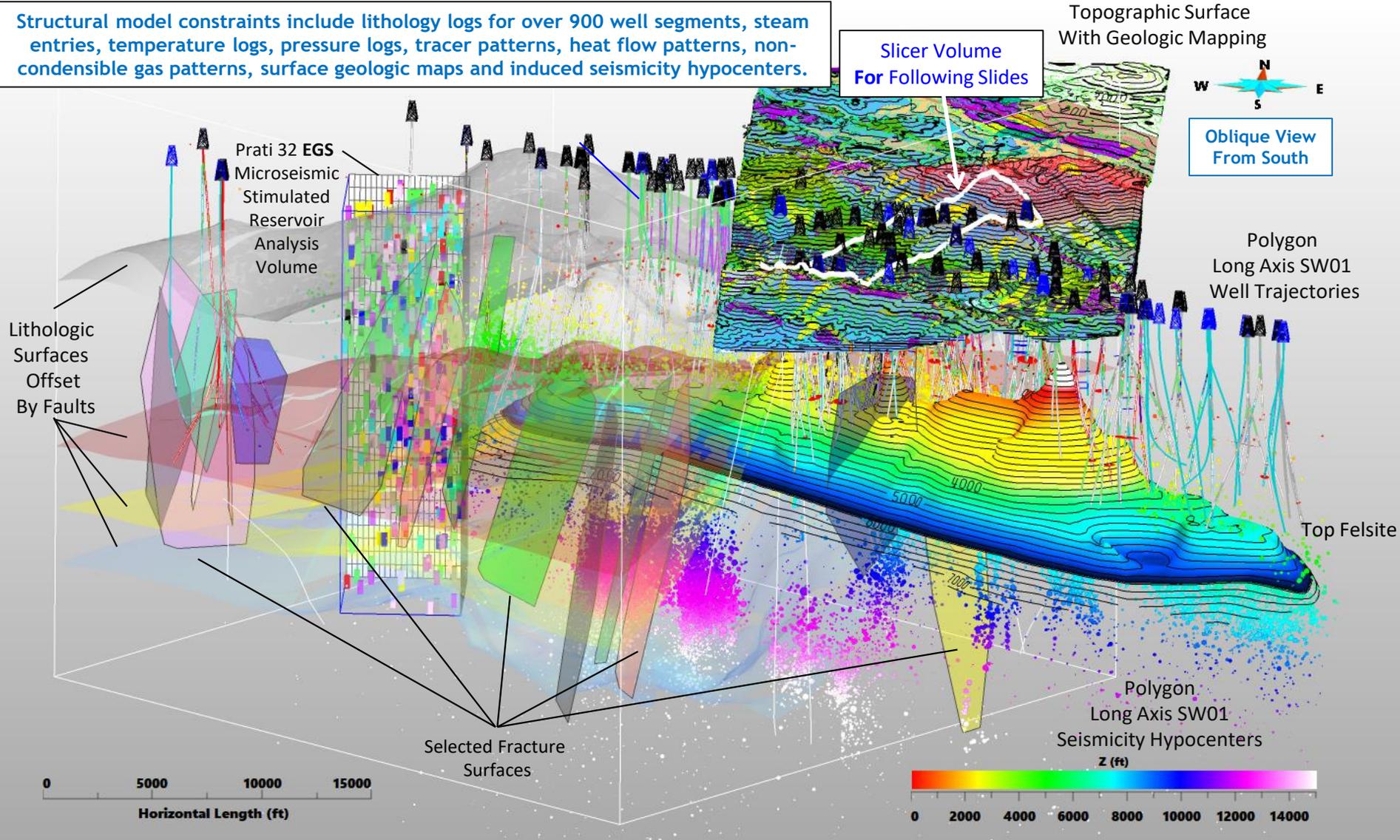
Fieldwide Water Injection Monthly Volumes And Induced Seismicity

Water Injection Wells Added Since January 2020 For Better Water Distribution And Seismicity Mitigation



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 900 well segments, steam entries, temperature logs, pressure logs, tracer patterns, heat flow patterns, non-condensable gas patterns, surface geologic maps and induced seismicity hypocenters.



* Subsurface Knowledge Unified Approach Geologic Object Computer Assisted Design

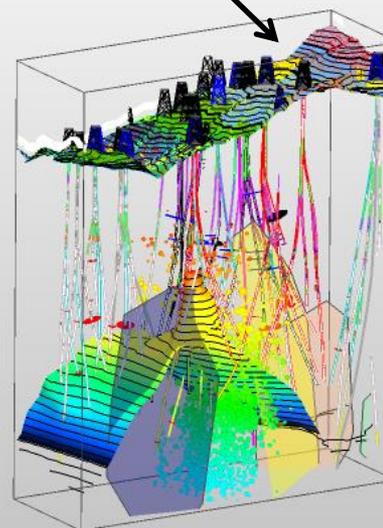
Slicer

Map View

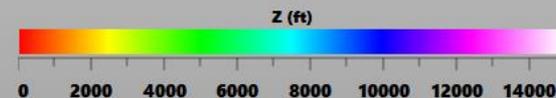
Slicer Volume
Used On Following Slides



0 5000 10000 15000
Horizontal Length (ft)



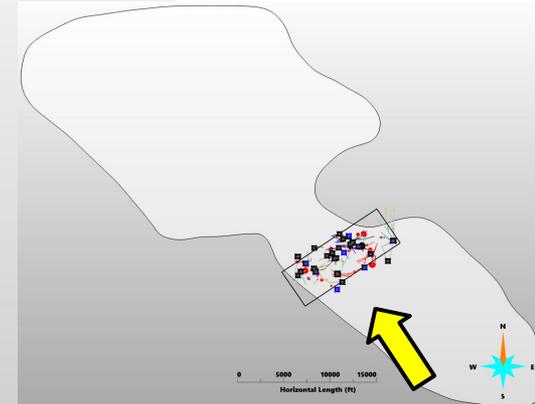
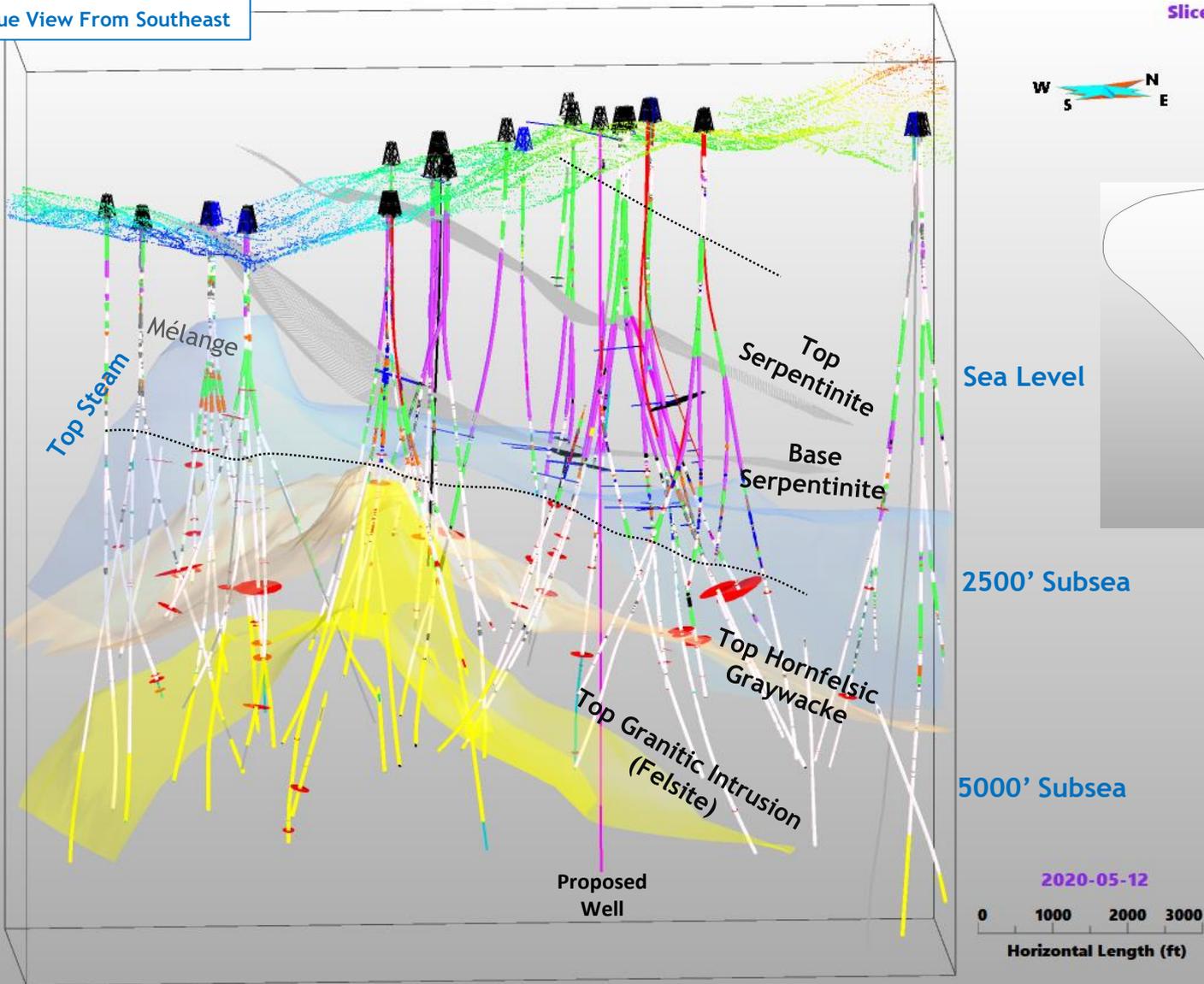
0 5000 10000 15000
Horizontal Length (ft)



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Proposed Water Injection Well Trajectory Within Geological Cross Section

Oblique View From Southeast



Primary Lithology Types

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

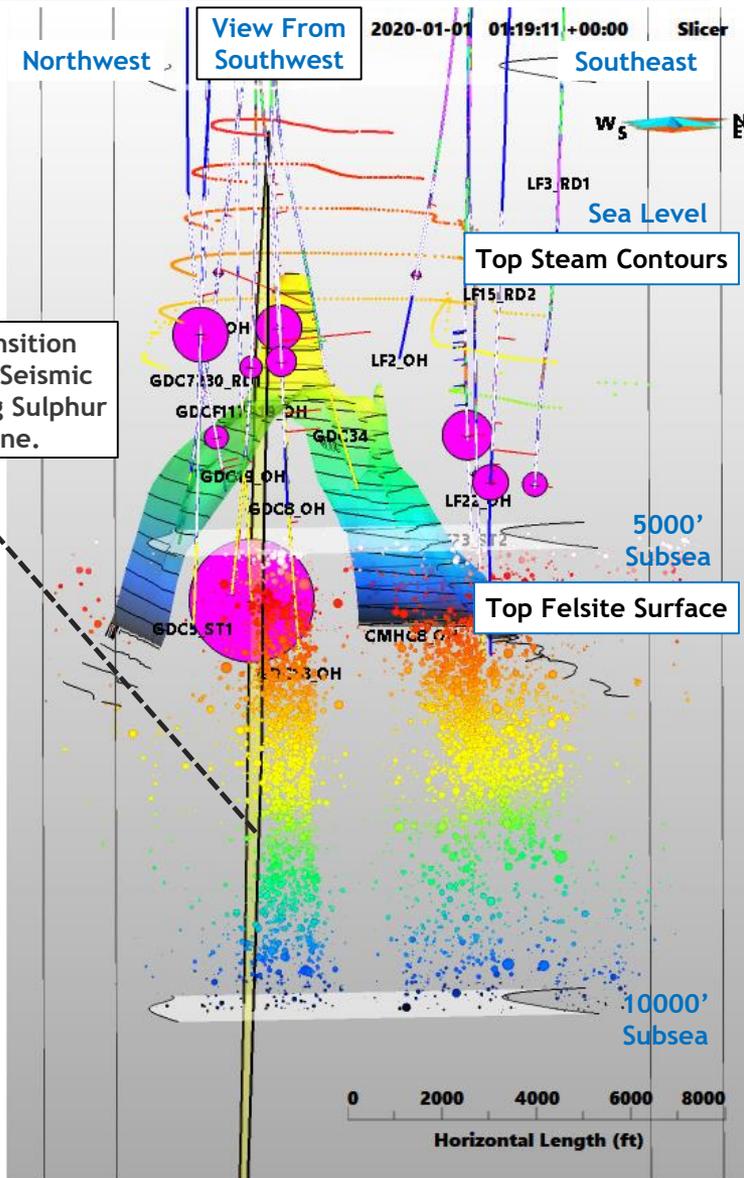
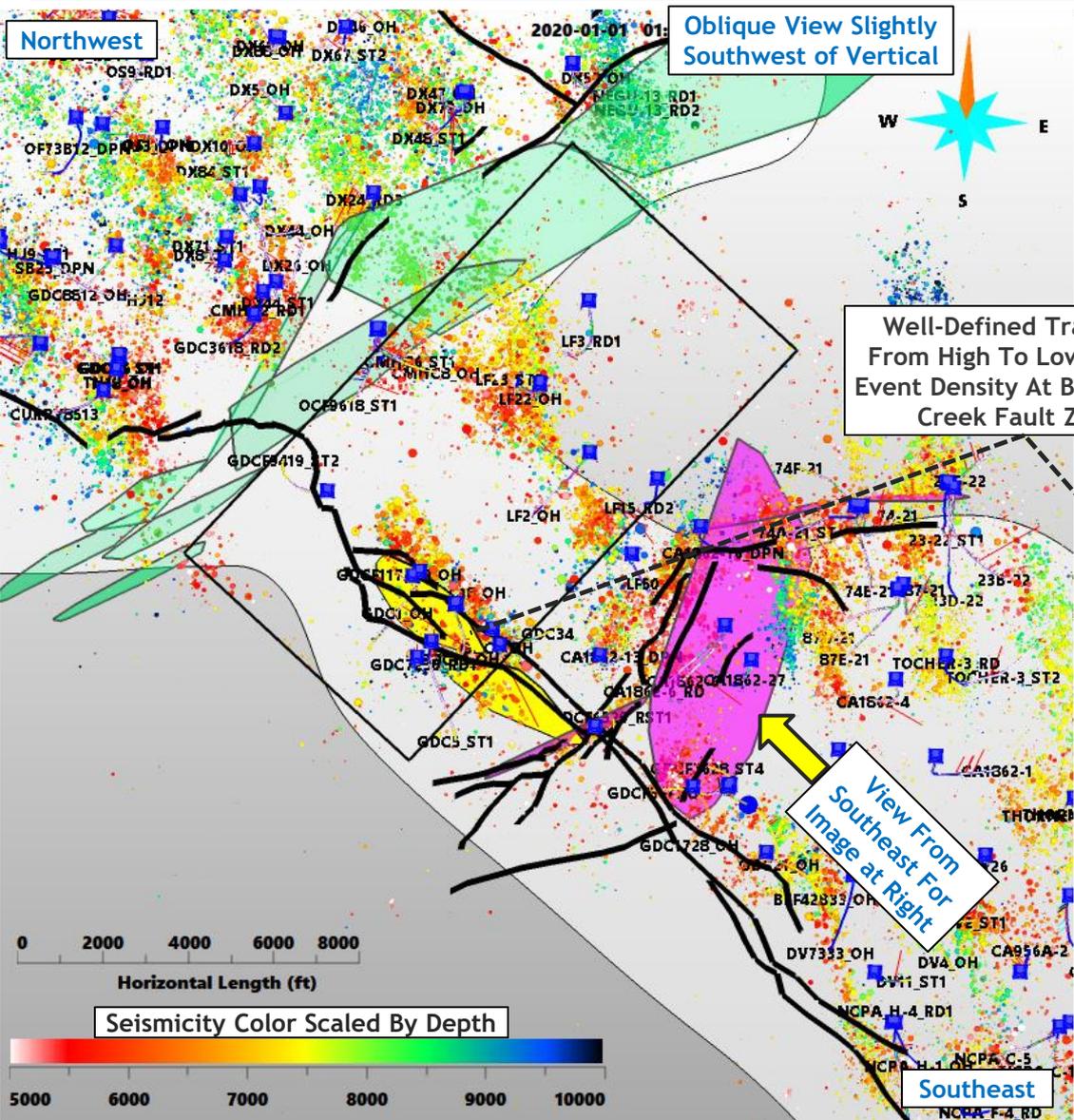
Toggle On/Off
To Distinguish

- Steam Entries
- Lost Circulation Zones

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Southwest Boundary of Structural Volume Define By Big Sulphur Creek Fault Zone

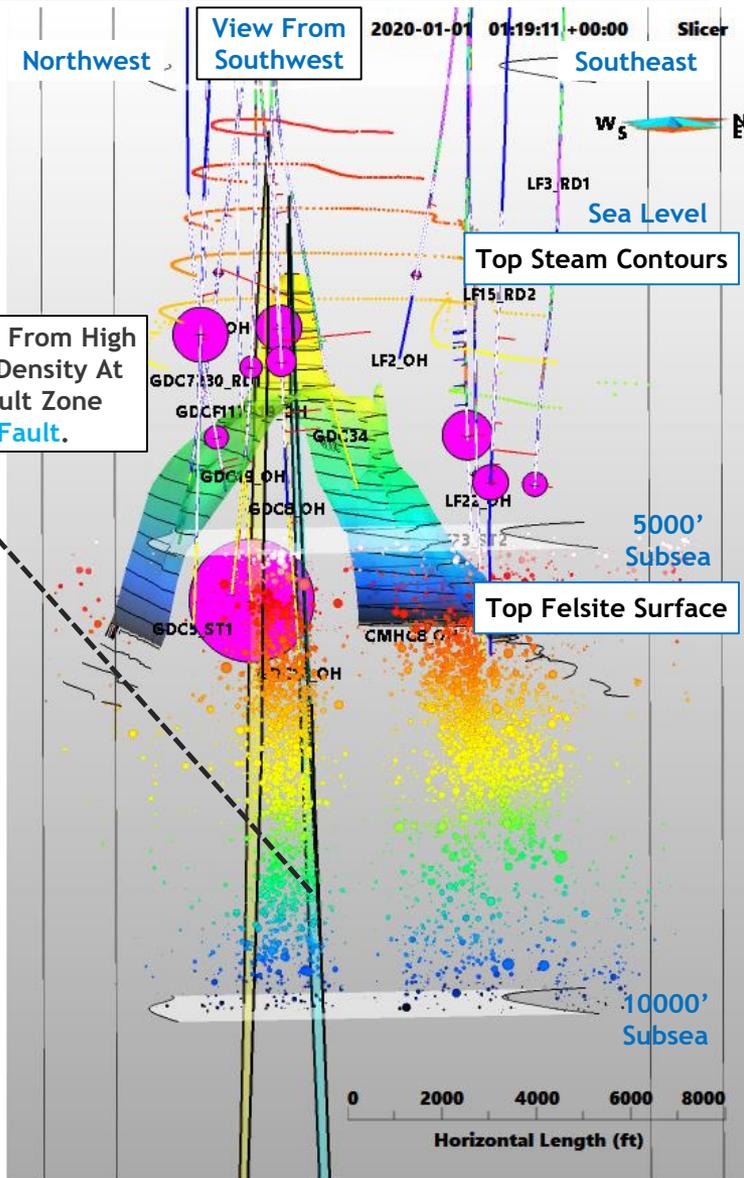
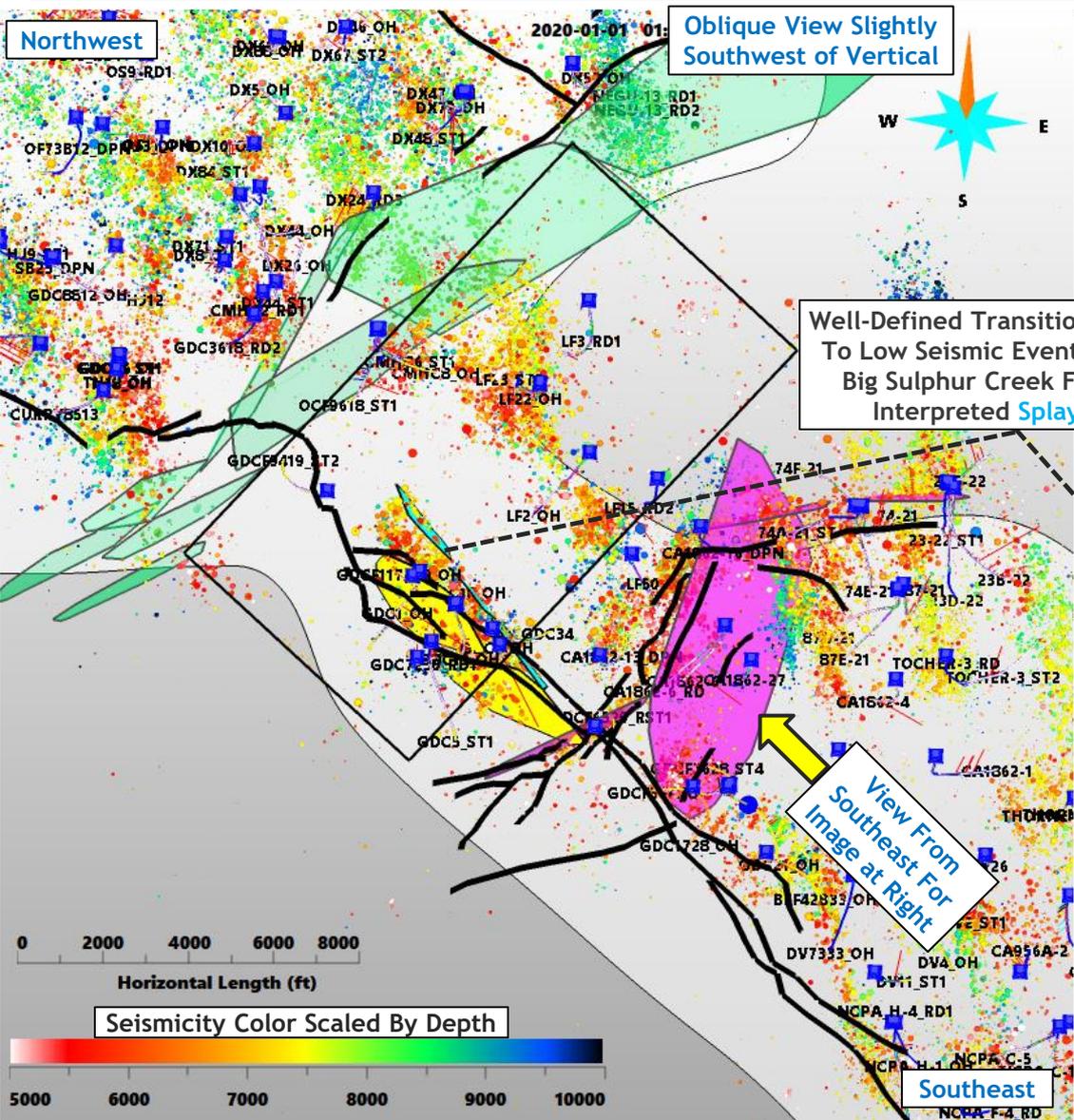
Fluid Flow Appears To Be Inhibited To The Southwest By Fracture Surfaces Associated With The Big Sulphur Creek Fault Zone



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Northeast Boundary of Structural Volume Define By Big Sulphur Creek Fault Zone Splay Fault

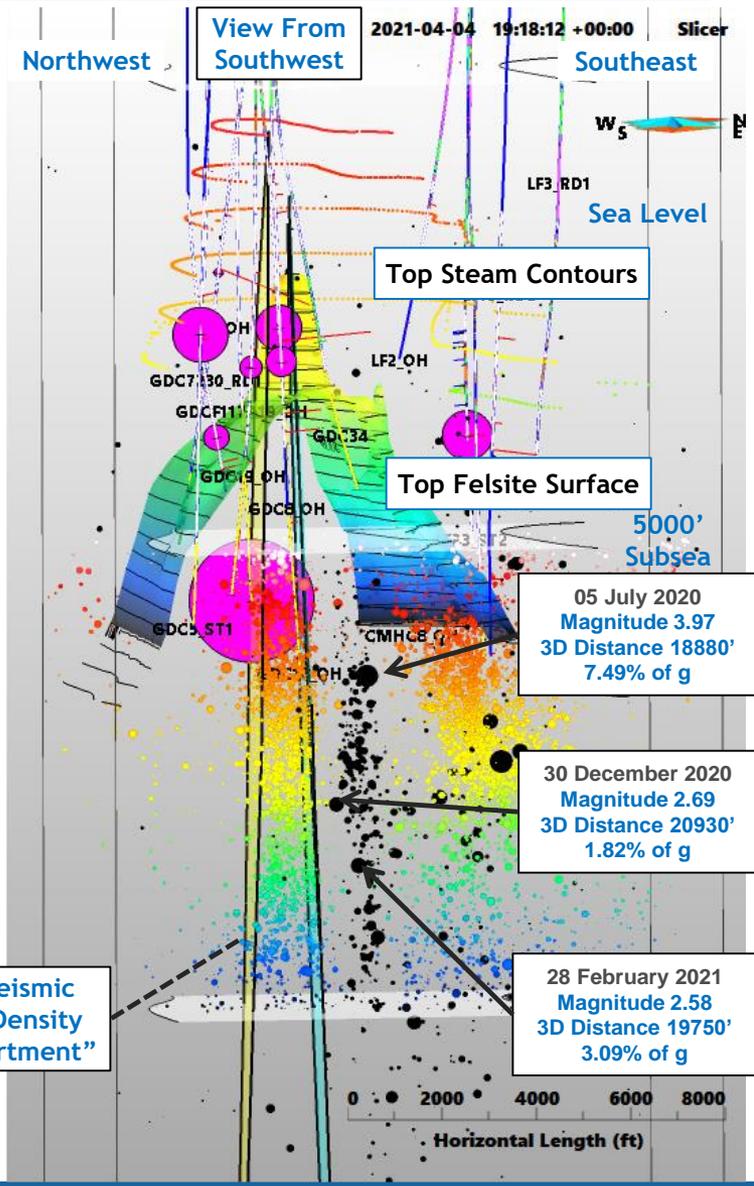
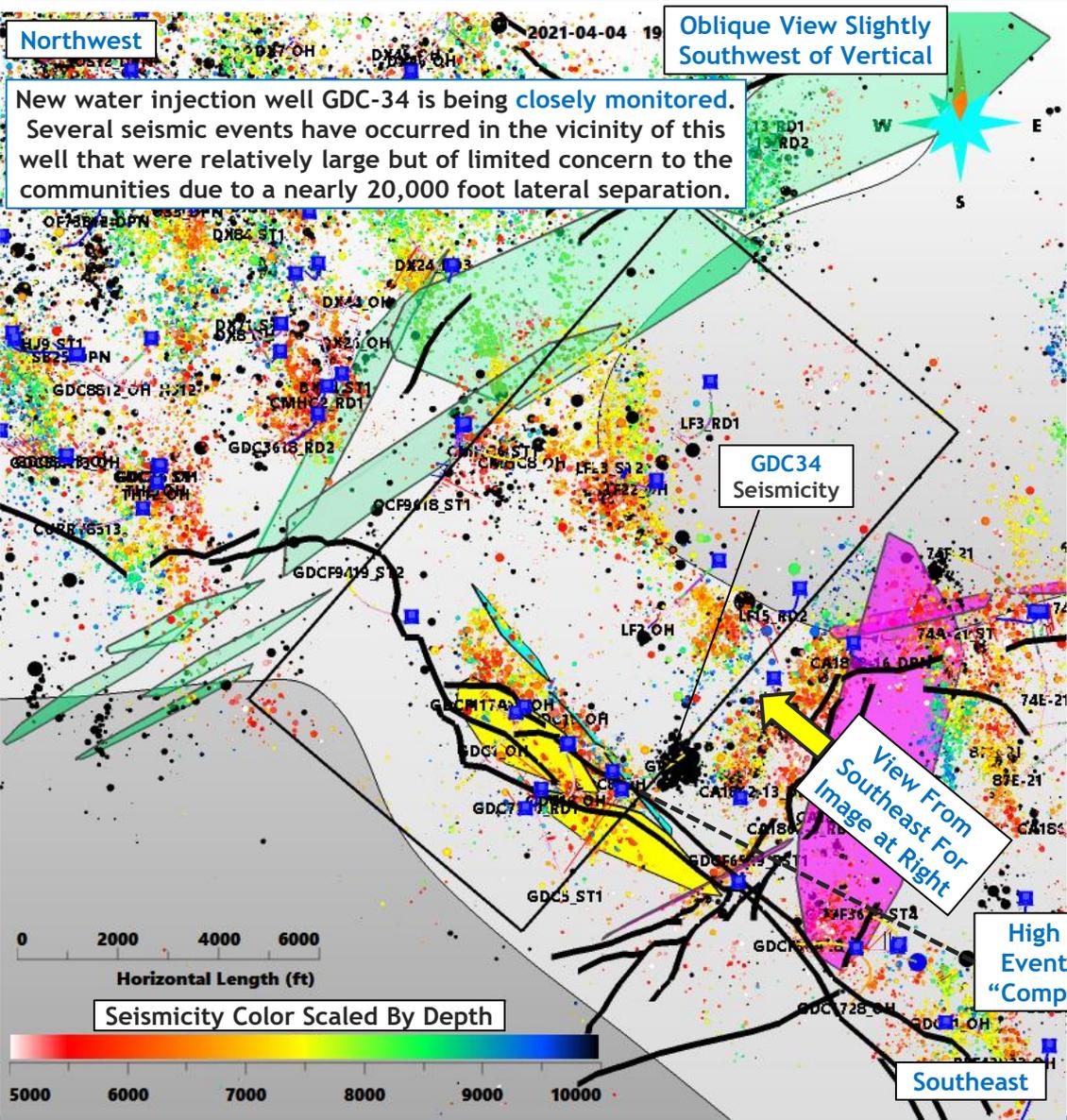
Fluid Flow Appears To Be Inhibited To The Northeast By A Fracture/Fault Splay System Associated With The Big Sulphur Creek Fault Zone



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Mapped Surface Faults, Subsurface Fractures/Faults And Reservoir Compartmentalization

2020 and 2021 Seismicity Illumination Shown As 2X Black Symbols To Highlight New Reservoir Recharge Volume From GDC34 Water Injection



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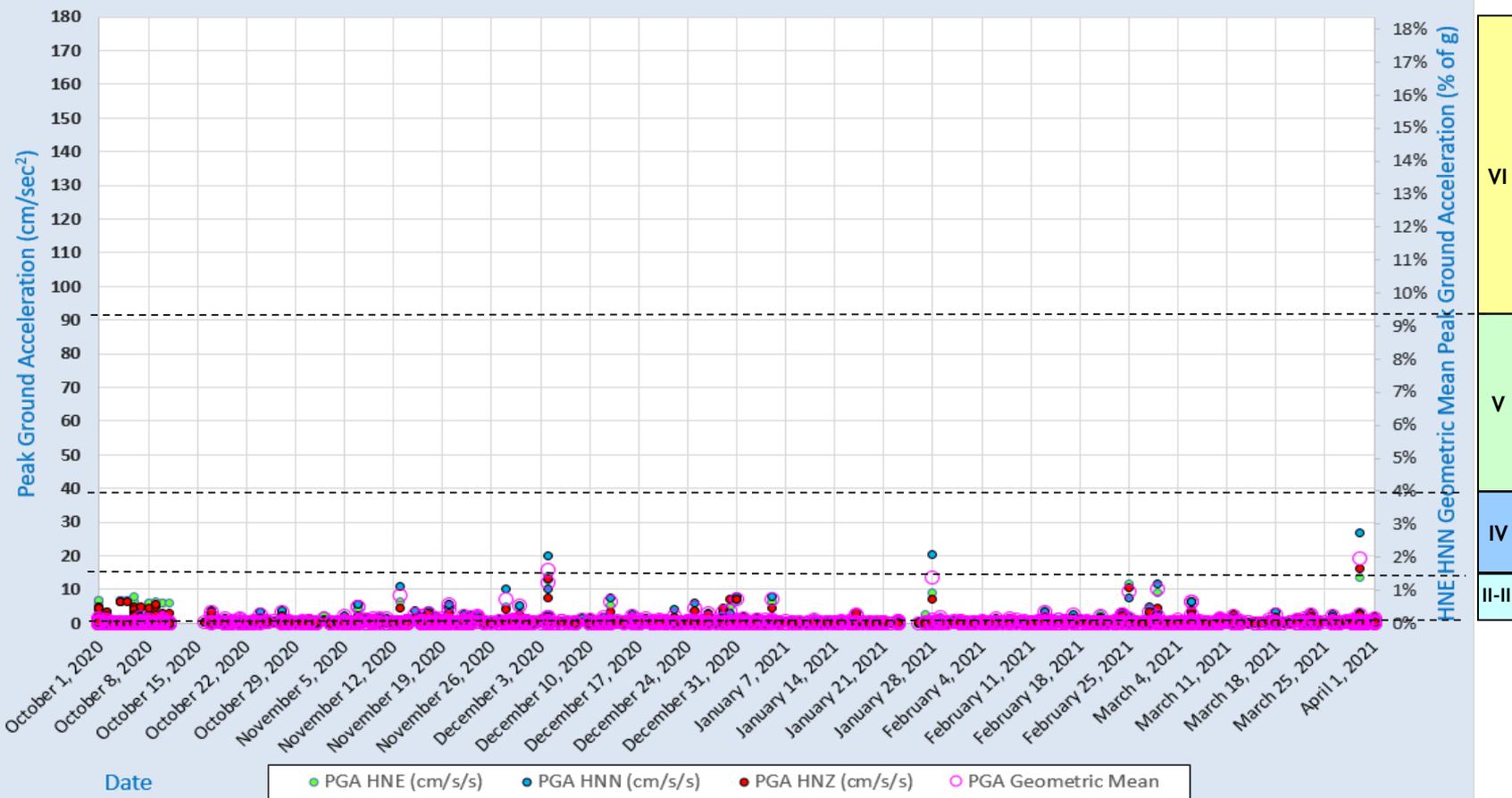
Cobb Area Alder Creek Strong Motion ACR

Cobb Strong Motion Data

Alder Creek ACR Northeast Geysers

Left Graph Axis - Peak Ground Acceleration - HNE East-West; HNN North-South; HNZ Vertical

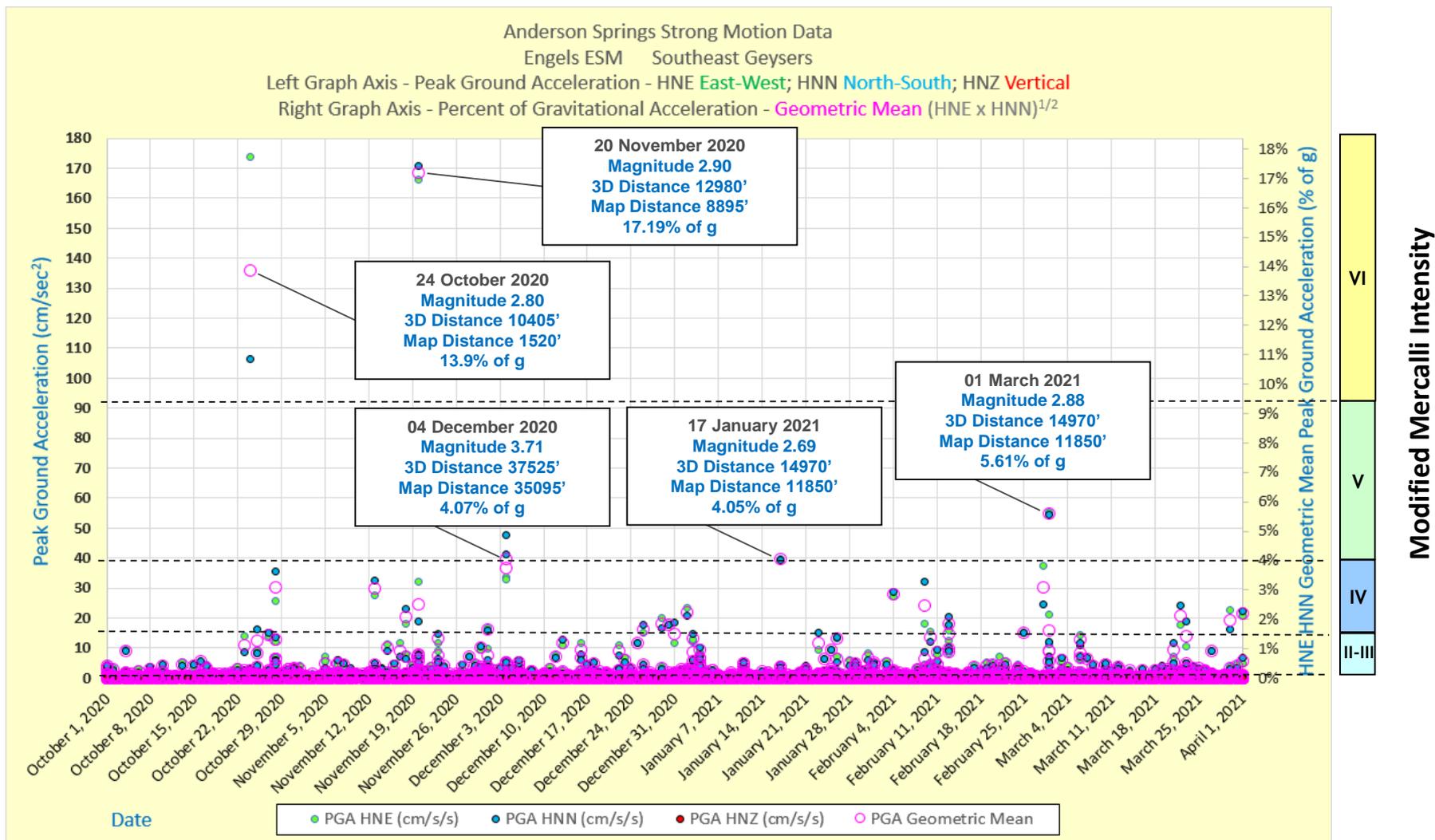
Right Graph Axis - Percent of Gravitational Acceleration - Geometric Mean (HNE x HNN)^{1/2}



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

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Anderson Springs Engels Strong Motion ESM

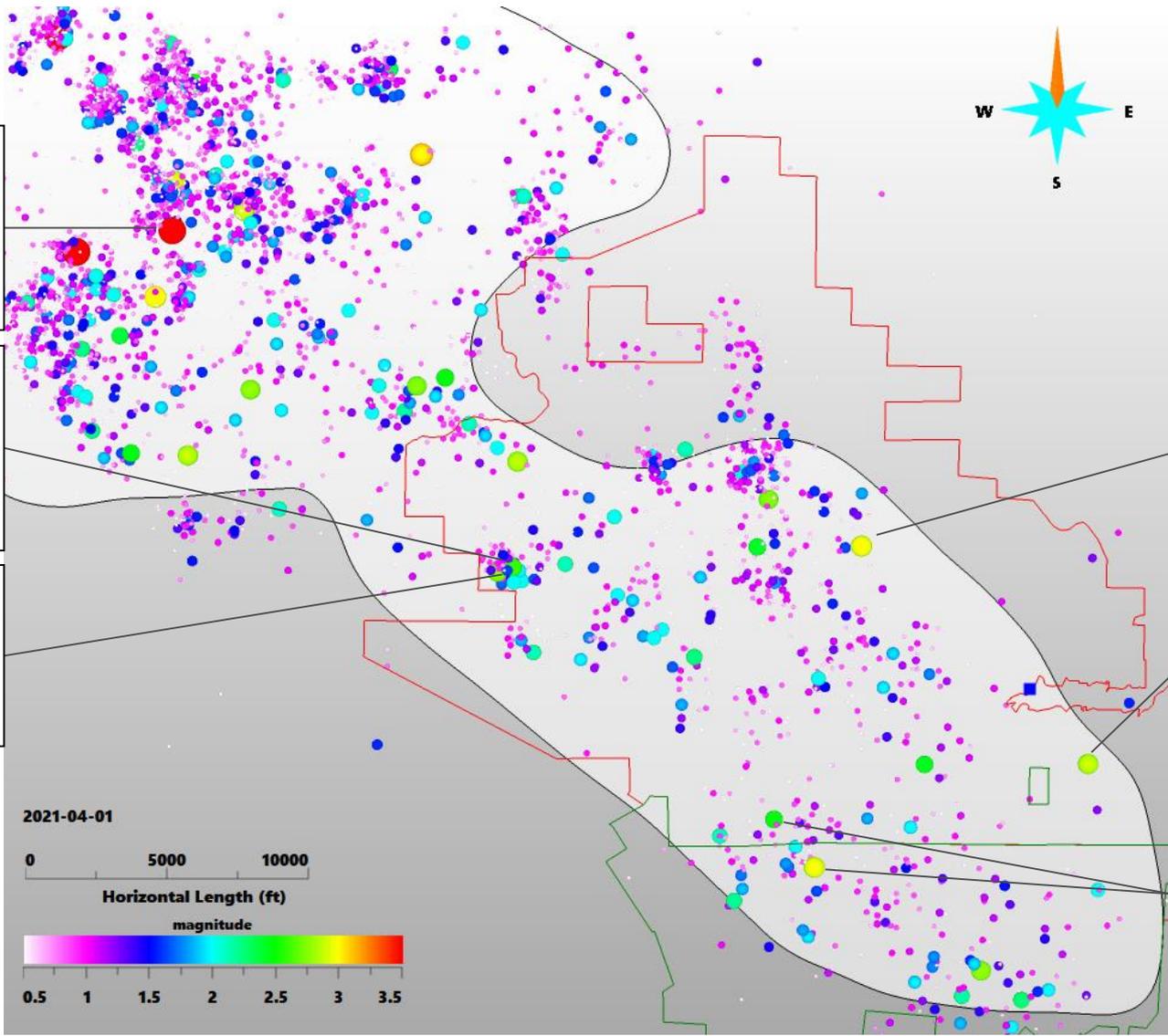


Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
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Modified Mercalli Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X

Seismic Monitoring Advisory Committee Meeting

Community Hotline

Seven Calls During The Reporting Period Of 01 October 2020 To 31 March 2021



04 December 2020
 Magnitude 3.71
 3D Distance 37525'
 Map Distance 35095'
 4.07% of g
 One Call
 Long Duration, Quite Strong

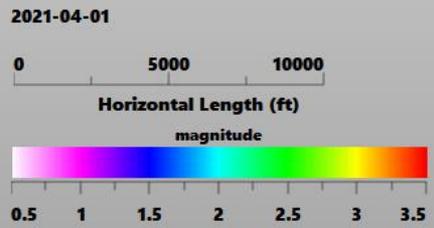
28 February 2021
 Magnitude 2.58
 3D Distance 19750'
 Map Distance 18640'
 3.09% of g
 One Call
 Small Event, Preceded By Rumbling

30 December 2020
 Magnitude 2.69
 3D Distance 20930'
 Map Distance 19120'
 1.82% of g
 One Call
 Large, Several Aftershocks

17 January 2021
 Magnitude 2.69
 3D Distance 14970'
 Map Distance 11850'
 4.05% of g
 One Call
 Short Duration, Really Shook Home Roof

24 October 2020
 Magnitude 2.80
 3D Distance 10405'
 Map Distance 1520'
 13.9% of g
 One Call
 Short Duration, Very Strong

01 March 2021
 Magnitude 2.47 / 2.88
 3D Distance ~15000'
 Map Distance 12000'
 1.63% / 5.61% of g
 Two Calls
 Two Moderate Events In Series, Second Stronger



Seismic Monitoring Advisory Committee Meeting

Seismicity AFTER 01 October 2021 Through 31 March 2021 Reporting Period

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, a primary goal of the analysis completed for this presentation is to be responsive to the community's concerns.

In April, 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 2.69

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

Events greater than magnitude 3.25 occur very infrequently in the southeast Geysers and resulted in 15 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 Calpine lease seismicity is discussed in detail within the remaining slides.

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

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

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

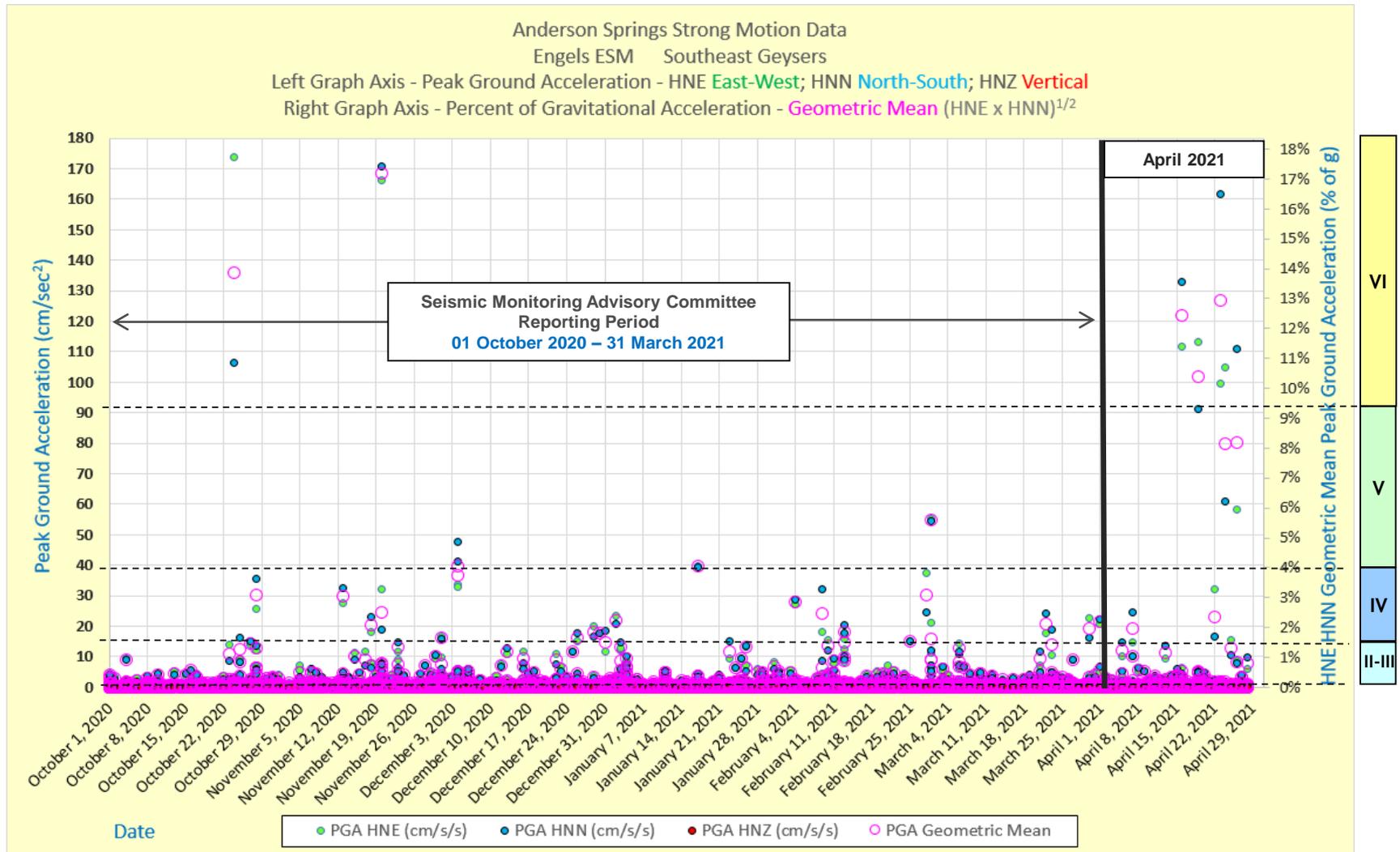
24 April 2021
Magnitude 2.69
3D Distance 10010 '
Map Distance 7750'
8.15% of g

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

Seismic Monitoring Advisory Committee Meeting

Anderson Springs Engels Strong Motion ESM

WITH APRIL 2021 - AFTER REPORTING PERIOD

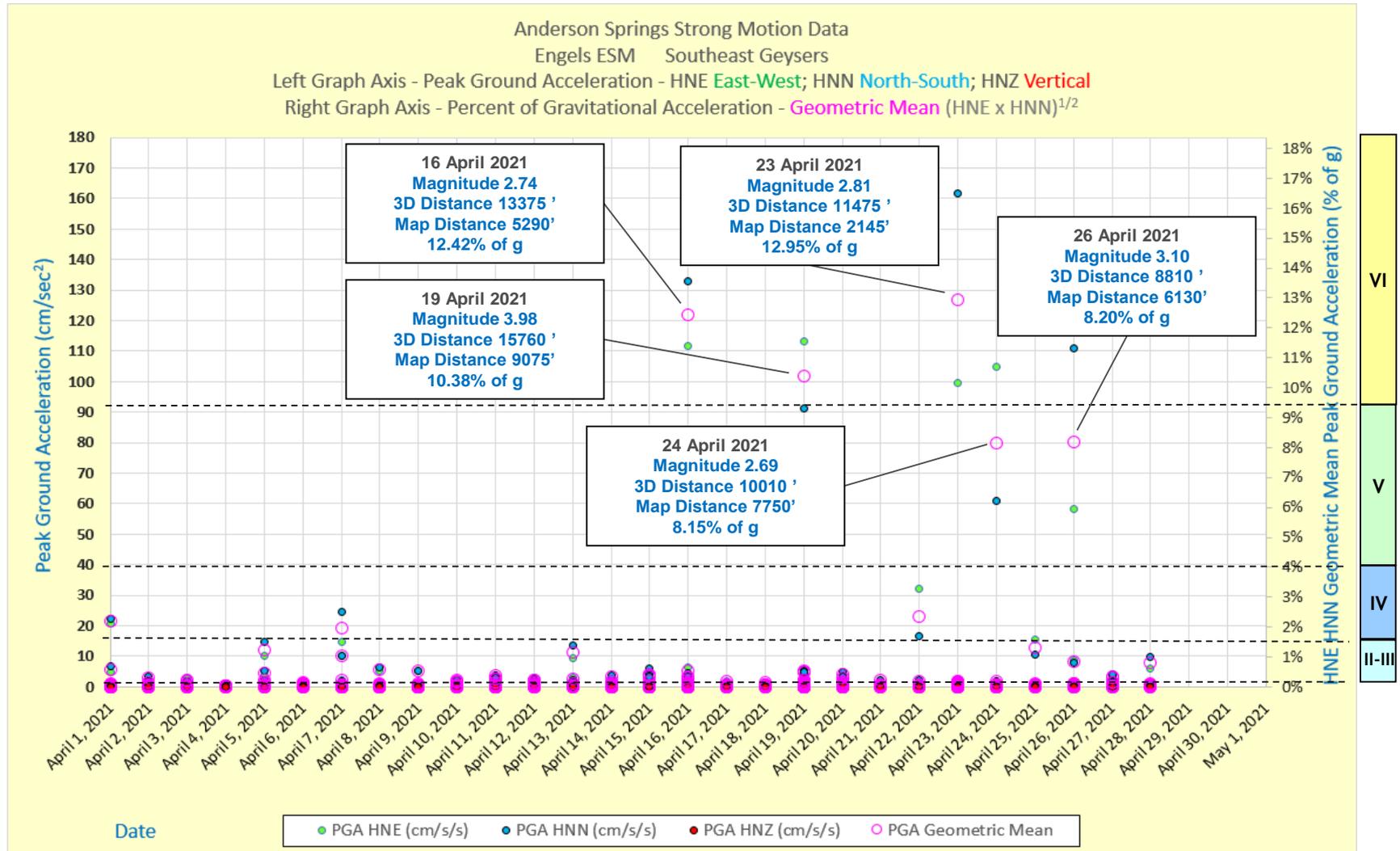


Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	None	None	None	Very Light	Light	Moderate	Mod/Heavy	Heavy	Very Heavy
Peak Acceleration (% of g)	< 0.17	0.17 - 1.4	1.4 - 3.9	3.9 - 9.2	9.2 - 18.0	18.0 - 34.0	34.0 - 65.0	65.0 - 124.0	> 124.0
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Modified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

Seismic Monitoring Advisory Committee Meeting

Anderson Springs Engels Strong Motion ESM

APRIL 2021 ONLY - AFTER REPORTING PERIOD

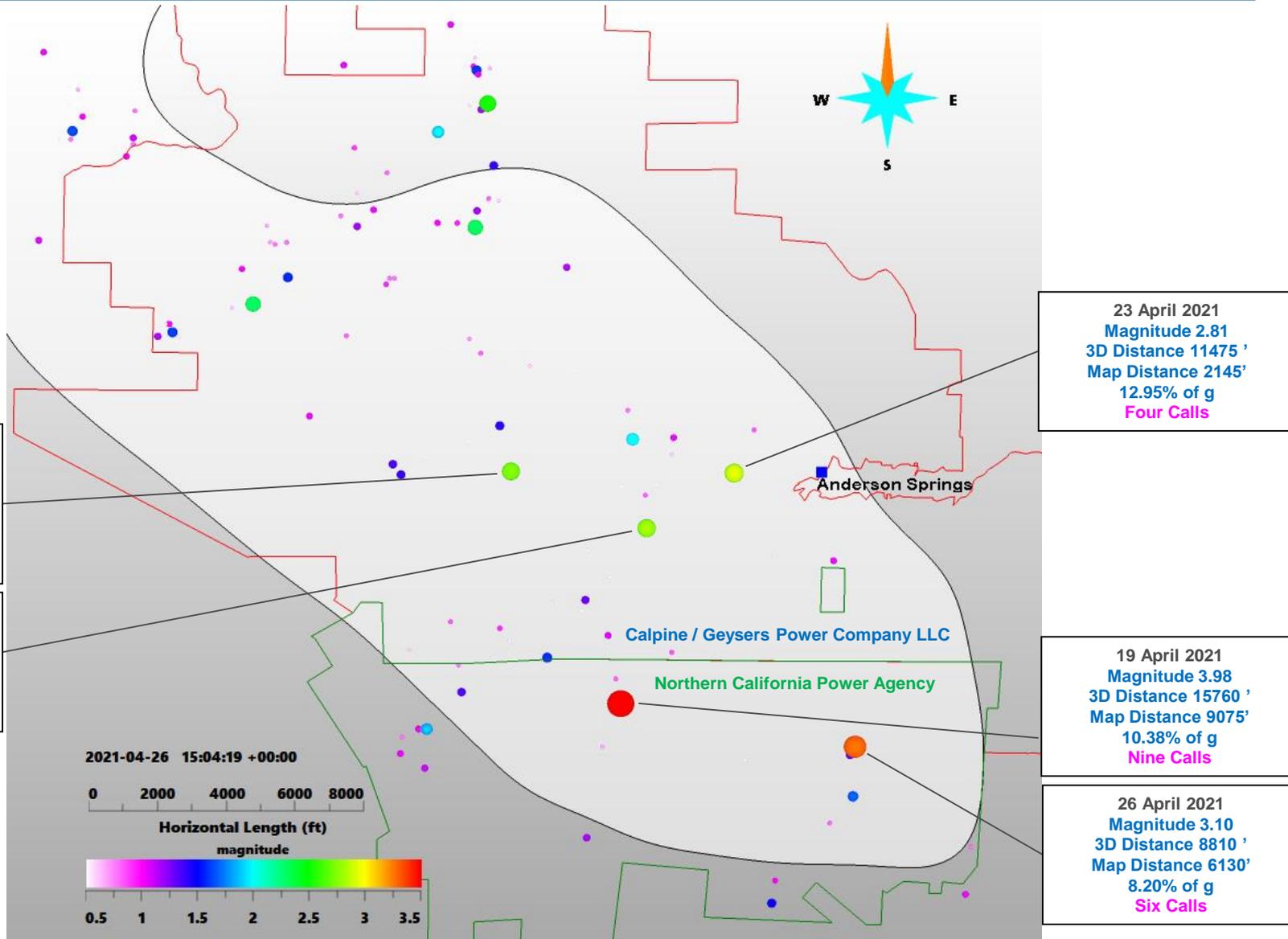


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Modified Mercalli Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X

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01 April 2021 to 30 April 2021 Seismicity In Map View

AFTER 01 October 2021 Through 31 March 2021 Reporting Period

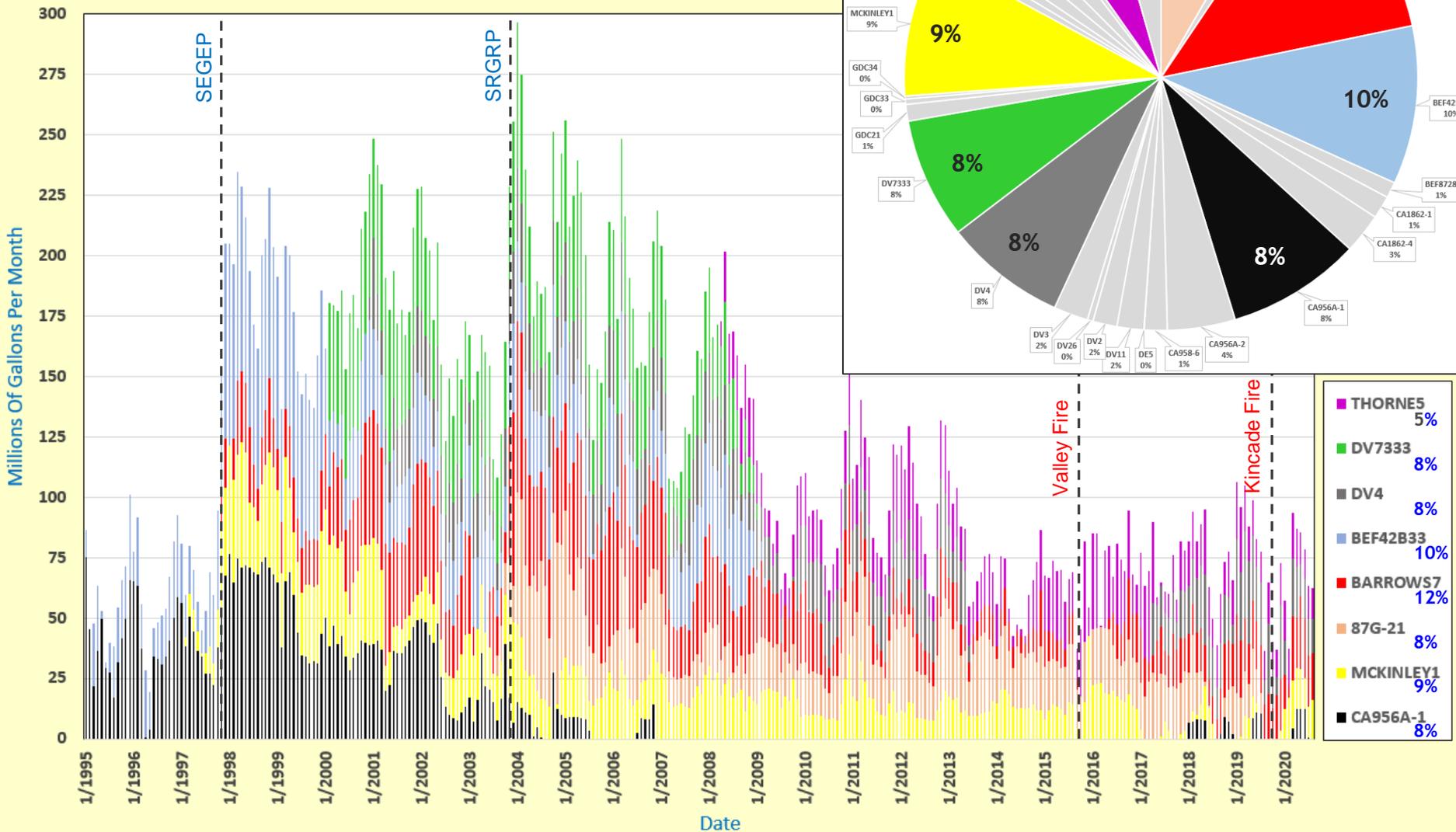


Seismic Monitoring Advisory Committee Meeting

Southeast Geysers Water Injection Wells

Time Series Limited To Wells $\geq 5\%$ of Total Volume

Water Injection Near Proposed McKinley 17 New Water Injection Well

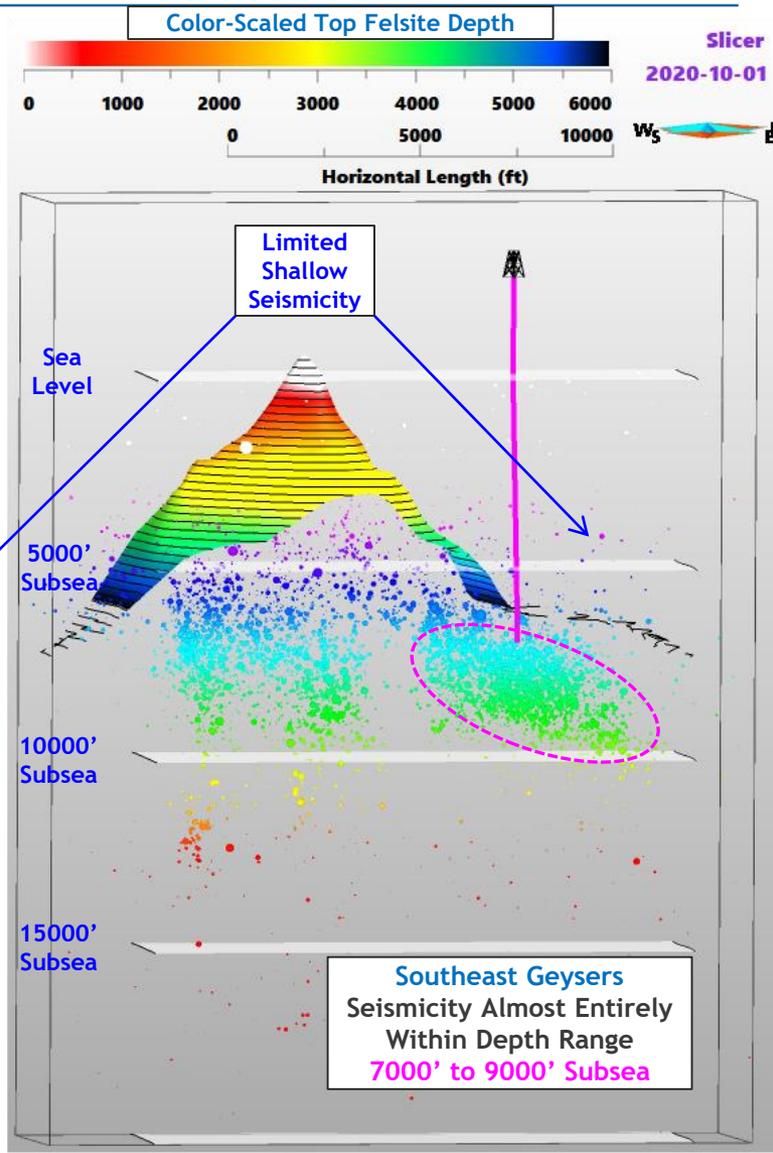
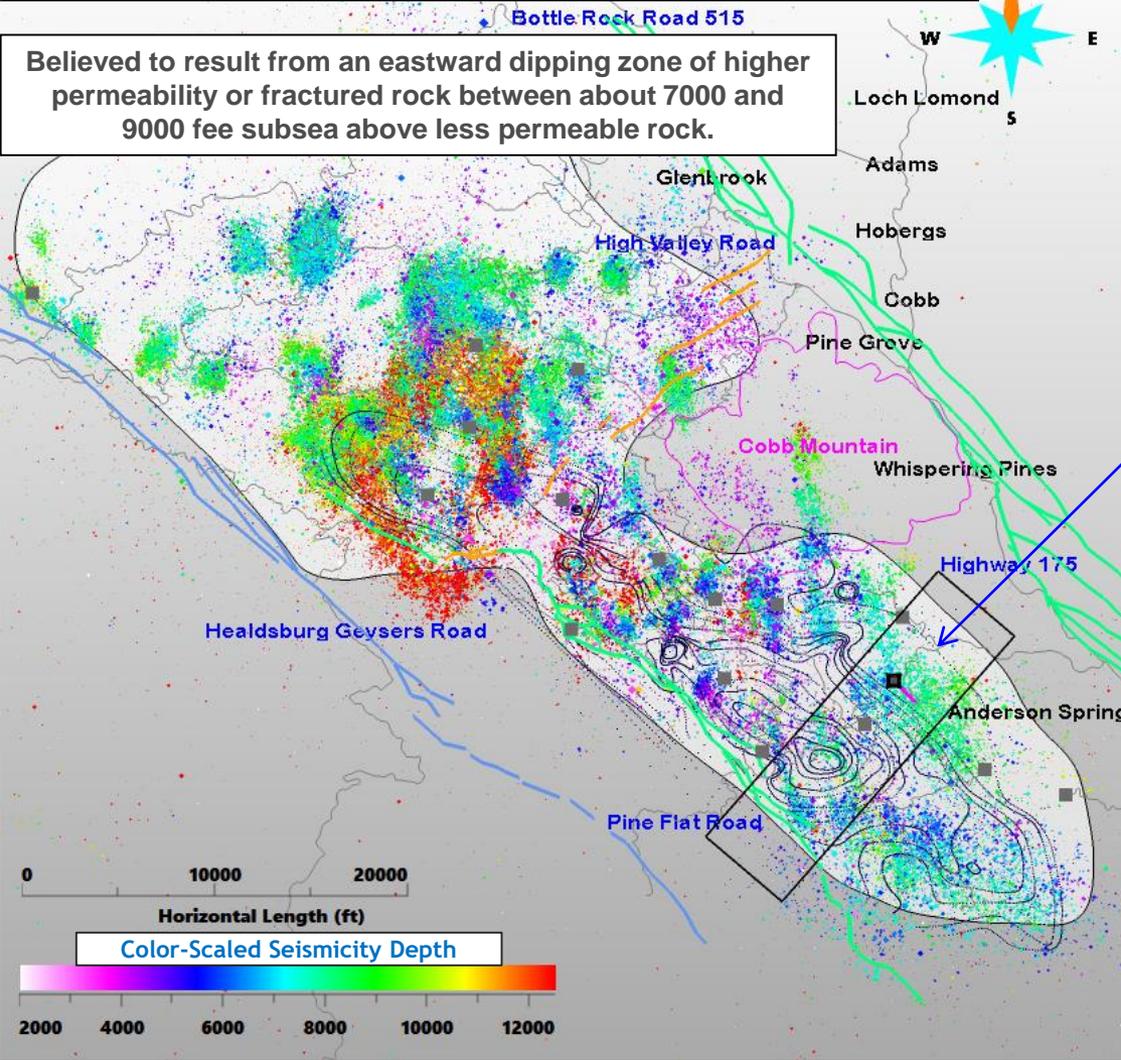


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Seismicity From 01 January 2005 – 01 October 2020 Shown

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 feet subsea above less permeable rock.



Seismic Monitoring Advisory Committee Meeting
Detailed Seismicity Analysis for 01 April 2021 to 30 April 2021 AFTER REPORTING PERIOD
 2019 and 2020 Seismicity As Light Gray Symbols
 2021 Seismicity **Color-Scaled** By Magnitude (and 2x Symbol Size)

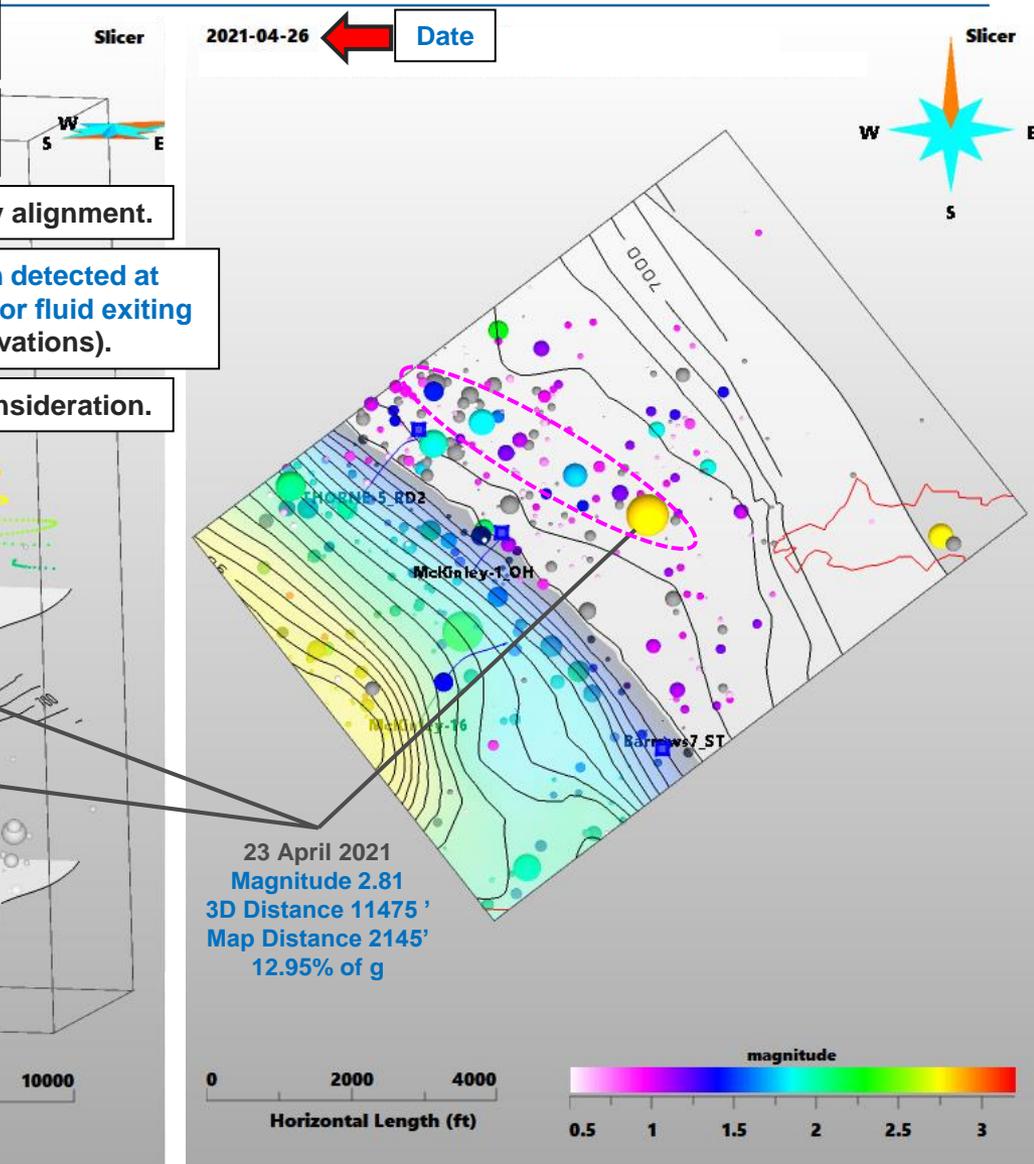
In early 2021 there were increased and variable injection rates at **Thorne-5, McKinley-1, McKinley-16** and **Barrows-7**.

Seismicity began to progress southeast from Thorne-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 Thorne-5 RD2 are now under consideration.



Seismic Monitoring Advisory Committee Meeting

Summary (1)

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](#).

In April, 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 2.69](#)

Magnitude	Number of Events
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≥ 4.0	0
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≥ 3.0	4
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≥ 2.0	78
≥ 1.5	310

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](#)

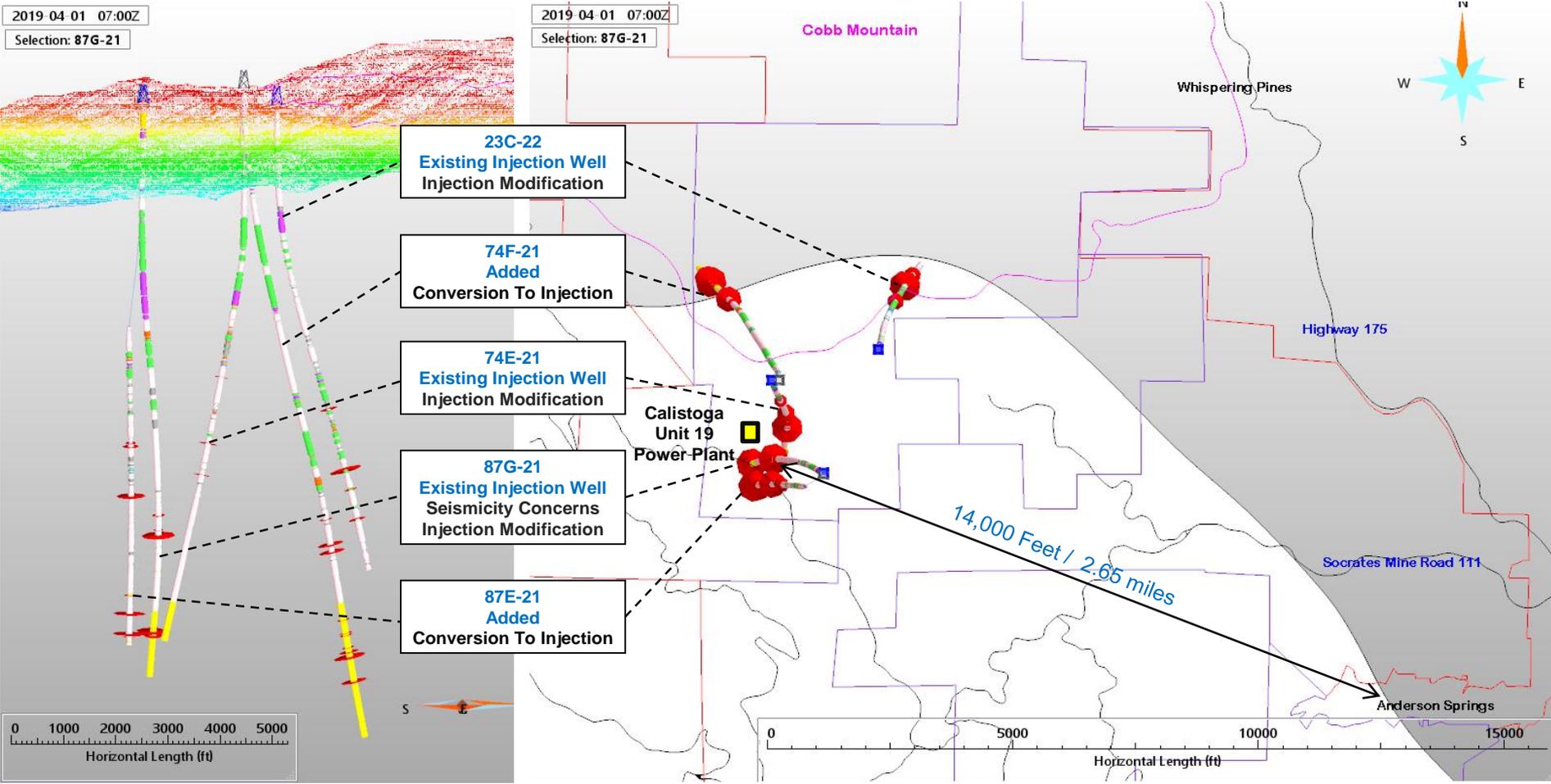
The seismicity occurring on the Calpine leases was carefully reviewed and modifications to the injection profiles for wells Thorne-5 RD2 and GDC-34 OH have been proposed.

Due to previous concerns with seismicity patterns and progression, modifications to water injection rates were proposed and completed for water injection well [Negu-13](#) in the northeast Geysers (350 gallon per minute limit) and water injection well distribution for [CA23C-22](#) / [CA74E-21](#) / [CA74F-21](#) / [CA87E-21](#) / [CA87G-21](#) in the southeast Geysers.

This improved southeast Geysers water distribution for seismicity mitigation is seen on next slide.

Calistoga Power Plant Area

- 74F-21 October 2019 Conversion of Steam Production Well to Injection
- 87E-21 November 2019 Conversion of Steam Production Well to Injection
- 23C-22 Early 2020 Modification to Existing Water Injection
- 74E-21 Early 2020 Modification to Existing Water Injection
- 87G-21 Early 2020 Modification to Existing Water Injection



Acknowledgements

Valuable guidance has been provided by [Dr. Ernie Majer](#) of Lawrence Berkeley National Laboratory, [Dr. David Oppenheimer](#) of the United States Geological Survey and [Dr. Roland Gritto](#) of Array Information Technology concerning The Geysers induced seismicity analysis, along with [Dr. Joe Beall](#) based on his extensive knowledge of The Geysers geology.

Summer Geophysics Interns [Rob Klenner](#), [Ramsey Kweik](#) and [Patrick Pierce](#) assisted greatly with the painstaking conversion of hard copy lithology logs and steam entry data to digital form.

Numerous geologists working over many decades for many employers created surface geologic maps throughout The Geysers. Specifically, [Mark Walters](#) created detailed North Geysers surface geologic maps.

AutoCAD and Access databases maintain by [Chuck Young](#) and [Pete Miller](#), respectively.

Summer Geoscience Intern [Corina Forson](#) merged the existing hard copy surface geology maps and completed some additional field mapping, resulting in a field-wide ArcGIS (digital) surface map compilation. Summer Geoscience Interns [Andrew Sadowski](#) and [Rowan Kowalsky](#) completed refinements to the field-wide ArcGIS (digital) surface map compilation.

Several subsurface lithology and reservoir transitions, such as the Top Felsite and Top Steam, were also defined by numerous geologists over many decades. Some primary contributors to AutoCAD contour line maps used as guidance during 3D model creation are [Dr. Joe Beall](#), [Mark Walters](#) and [Melinda Wright](#).

Installation and maintenance of a reliable LBNL seismic monitoring network has been provided primarily by LBNL contractor [Ramsey Haught](#).

Seismic waveform data, metadata, or data products for this study were accessed through the [Northern California Earthquake Data Center](#) and the [Lawrence Berkeley National Laboratory](#) seismicity database. requirements and hardware specifications.

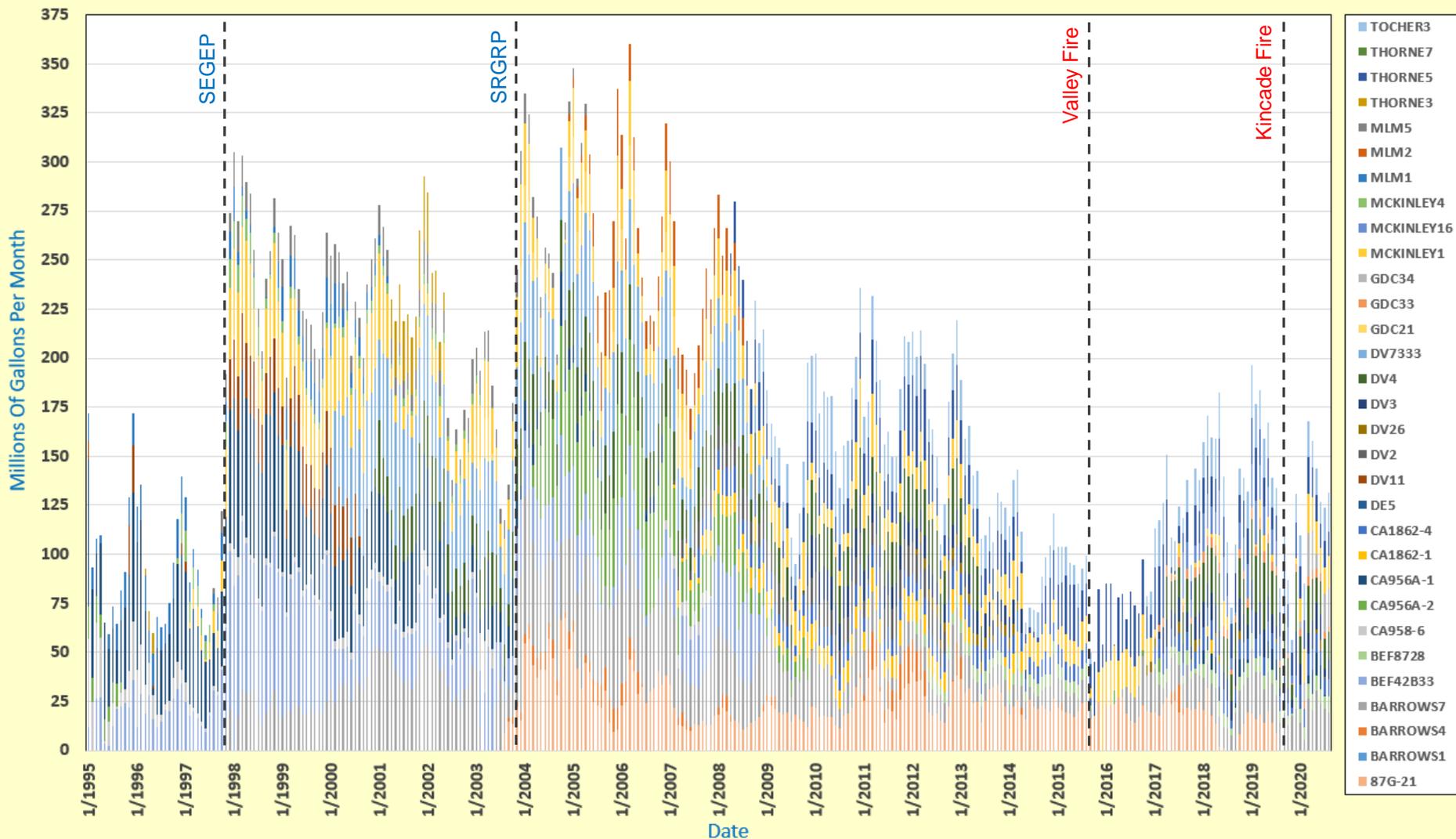


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Southeast Geysers Water Injection Wells

Time Series Since 1995

Water Injection Near Proposed McKinley 17 New Water Injection Well



Seismic Monitoring Advisory Committee Meeting

Southeast Geysers Water Injection Well Thorne-5

Axis: 1 | GY.GY.BG_99_INJ_THORNE5_FR_AA | Range: Fixed *- 1d | All Points | 01:00:00 | Auto Update | Graph Properties | Apply | Excel

+ Add Axis | + Add Point | - Remove Axis | + Add Equation | - Remove Point | Start: 10/ 1/2020 12:00:00 AM | Shift Left | Shift Right | Average | Rate (sec): 60 | Run

Thorne-5 RD2 Water Injection
Daily Rates In Gallons Per Minute

