Seismic Monitoring Advisory Committee Meeting

01 April 2019 to 30 September 2019 Reporting Period

Calpine Geothermal Visitors Center

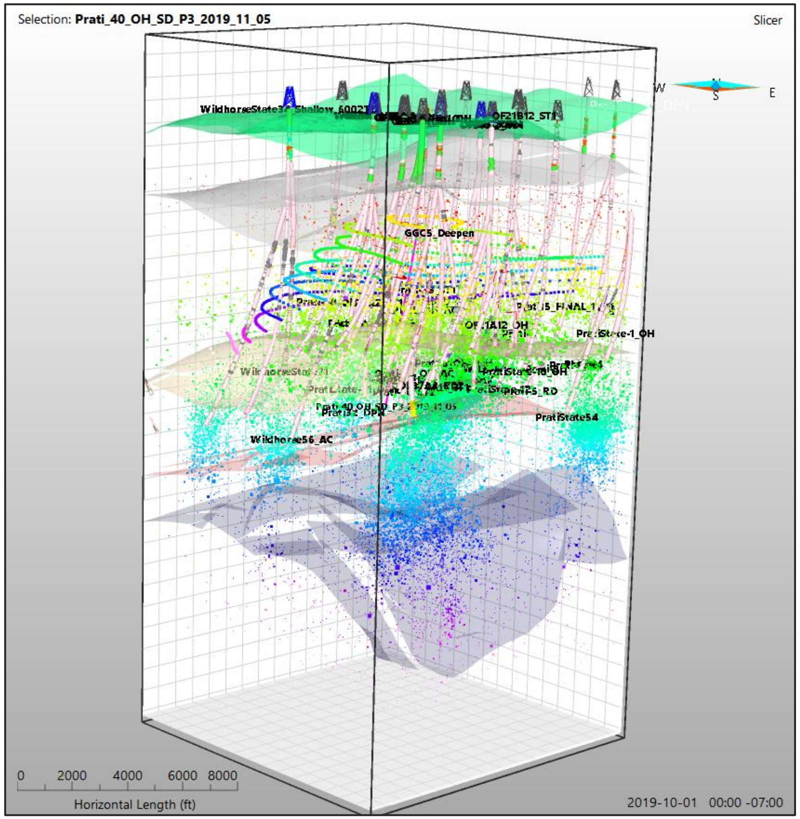
Middletown, California

12 December 2019

Craig Hartline Senior Geophysicist Calpine Corporation The Geysers

Seismic Monitoring Advisory Committee Meeting
Calpine Presentation Agenda
Reporting Period: 01 April 2019 to 30 September 2019

- Geysers Geothermal Field and Nearby Communities
- Status of Seismic Monitoring Networks
  - LBNL Seismic Monitoring Network
  - USGS / Northern California Seismic Network
  - Strong Motion Network
- Kincade Fire Summary
- Yearly Field-wide Water Injection and Seismicity
- Fieldwide Seismicity Analysis
- Water Injection and Induced Seismicity Animations
- Community Hotline
- Plate Tectonics and Regional Geology
- 3D Structural Model Building
  - Fault/Fracture Analysis
  - Compartmentalization
  - Well Planning Examples
- Additional Seismic Monitoring and Research

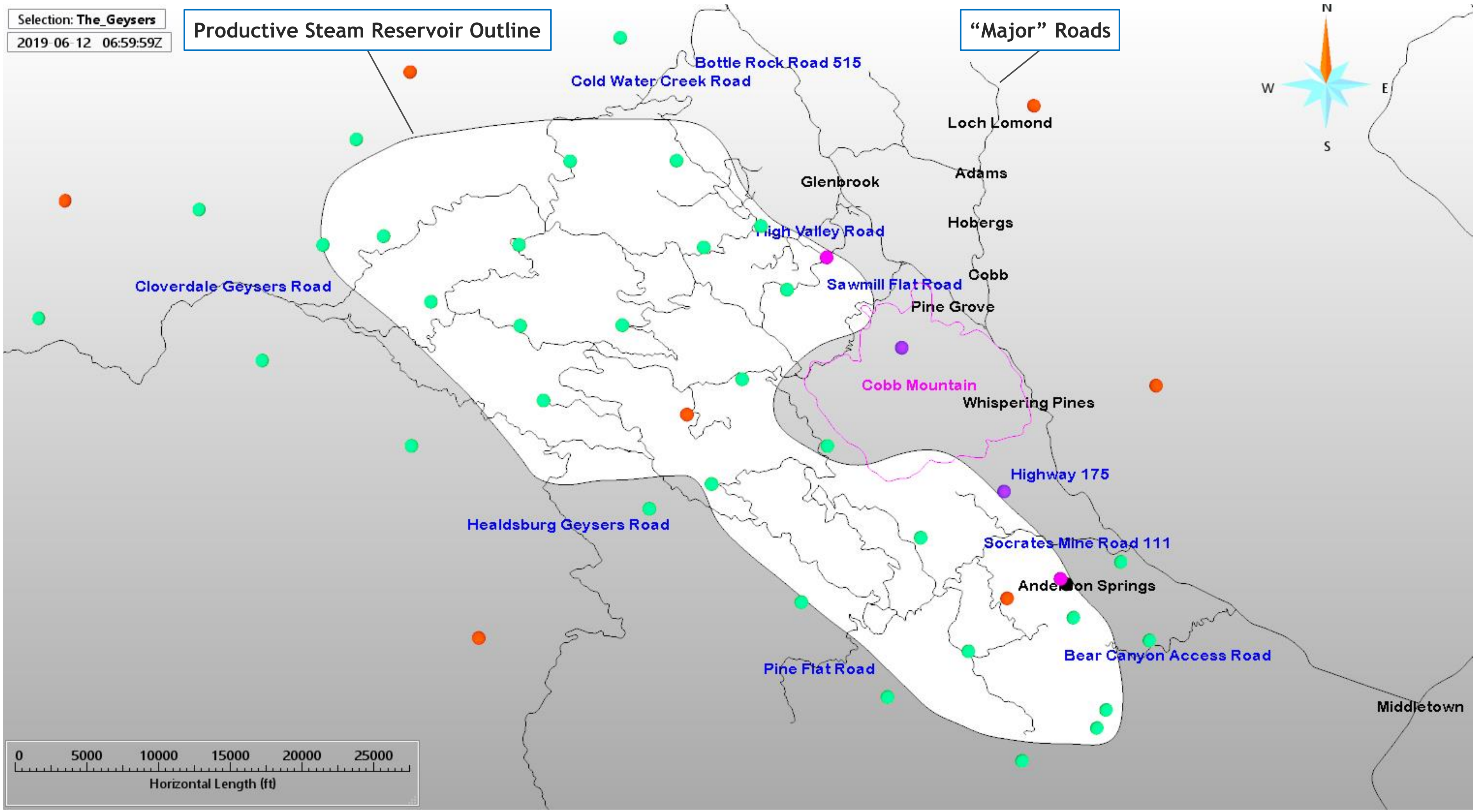


Geysers Geothermal Field, Nearby Communities and Seismic Monitoring Networks

Lawrence Berkeley National Laboratory
2003 installation; continuing upgrades
34 stations

Strong Motion Accelerometers
- 2018 Q1 Nanometrics installation (2)
- 2019 Q4 Nanometrics installation (2)
- 2003 ETNA installation; unreliable/replace

US Geological Survey Regional Network
1970's installation; several upgrades
7 contributing stations



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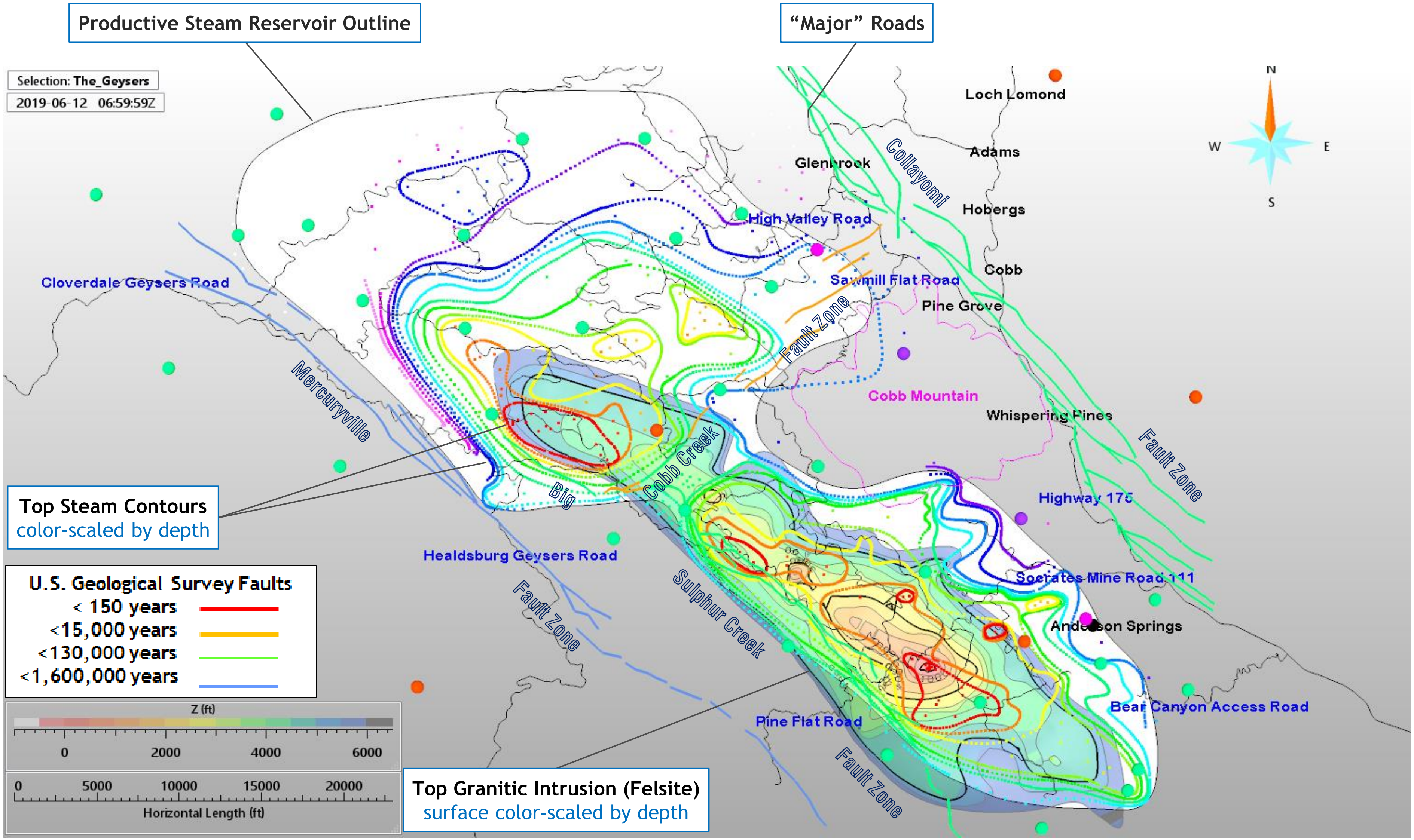
Geysers Geothermal Field, Top Granitic Intrusion and Top Steam Reservoir



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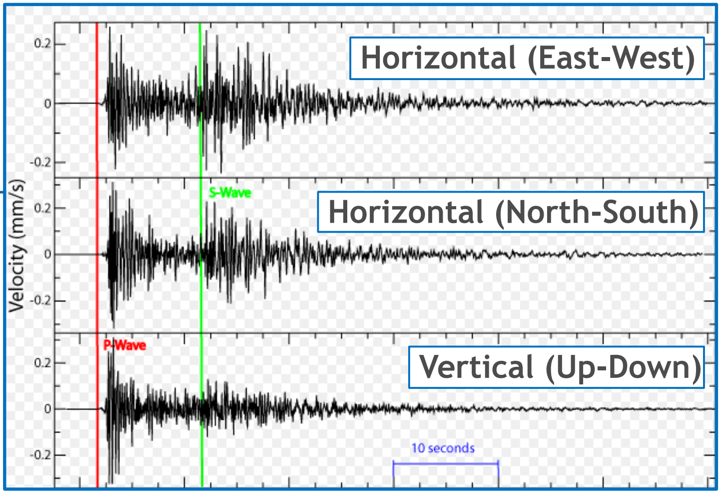
Status of Seismic Monitoring Networks



LBNL Seismic Monitoring Network

Fully Functional
Four Recent Concerns and Solutions

1. **Seismic Sensor Failures**
   - Calpine Purchased 24 Three-Component Geospace 2 Hz Sensors
   - 31 October 2019: 14 Sensor Replacements Completed
   - 31 December 2019: 24 Sensor Replacements Planned

2. **Department of Energy Network Support Ended May 2019**
   - 2019: Calpine contribution of $75,000 for network maintenance and upgrades.
   - 2020: Calpine contribution of $110,000 for yearly maintenance and upgrades.

3. **Seismic Monitoring Network Improvements**
   - Ramsey Haught primarily responsible for network installation, maintenance and upgrades.
   - Very specialized skills and Geysers experience difficult to replace upon upcoming retirement.
   - Calpine is completing 15 network upgrades to improved network reliability and data quality with:
     - Ramsey Haught El Sobrante, CA ~85 miles
     - Jarpe Data Solutions* Prescott Valley, AZ ~825 miles

   Goals: Improved reliability prior to Ramsey Haught retirement.
   Transition to Jarpe Data Solutions; Calpine staff trained for many on-site tasks.

4. **Kincade Fire**
   Sensor station damage; power and communication failures (began 23 October 2019 – after reporting period)

* Jarpe Data Solutions has existing relationship with LBNL concerning seismic acquisition testing and seismic databases

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Individual Sensor Component Failures

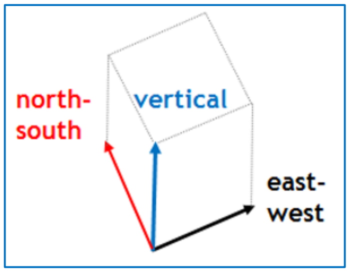
LBNL Seismic Monitoring Network

Individual components "sticking"
Upgrades to improve data quality and reliability

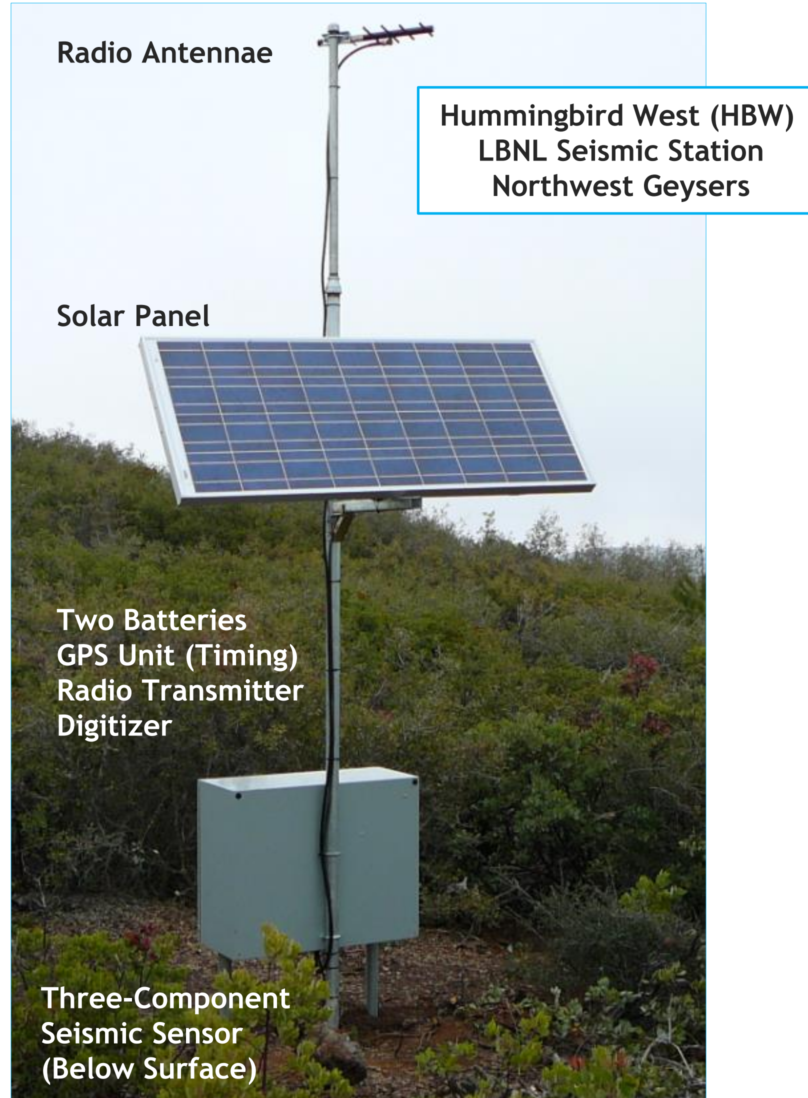
Geospace HS-1 3C arrays and cables

- Equipment: $2,400 per sensor station
- Installation: $ 500 per sensor station
- Total: $2,900 per sensor station

HS-1 3 Component Array



"ideally suited for seismological, engineering, and scientific applications where passive, low noise, short period, tri-axial sensors are required"



Seismic Monitoring Network Improvements
Upgrades In Progress

Geospace 2Hz Seismic Sensor Upgrades
- Upgrade 24 seismic monitoring stations to Geospace 2Hz sensors by April 2019

Strong Motion Station Installation
- Two additional Nanometrics Titan accelerometer stations (four on eastern perimeter near communities)

Borehole Seismic Sensor Installation
- Determine optimal downhole seismic sensor
- Upgrade downhole sensors (~10) for available shallow boreholes (≤ 500' depth)

Battery Replacement and Recycle
- 34 seismic monitoring stations
- 2 Sunlyte deep cycle batteries per station (76 total)

Hardware and Data Security
- LBNL server remote access – power plant firewall / security issues

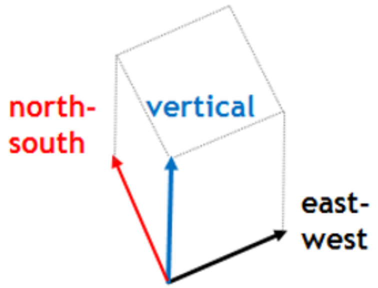
Software Upgrades
- Improvements to web-based strong motion data interface
- Improvements to waveform visualization software

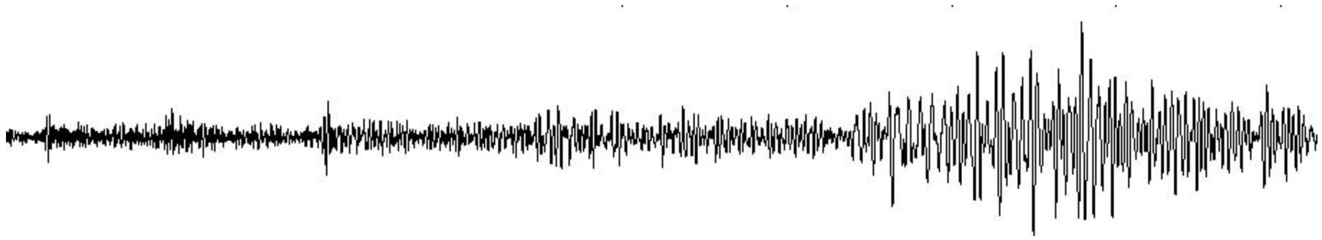
Data Quality and Continuity
- "State of Health" tracking for data servers and seismic monitoring stations
- Transition to data transfer, processing and storage by Jarpe Data Solutions
- Eliminate noise spikes on 2 Hz sensor data (grounding issue)
- Disk data back up systems for:
  - Geysers-based server
  - Jarpe Data Solutions server
- Power back up systems (UPS Uninterrupted Power Supply) for:
  - Geysers Administration Center servers
  - Radio Repeater, Microwave Repeater and Socrates Container (considering solar panels for extended power outages)

USGS*/ Northern California Seismic Network

The USGS and collaborating agencies provide services of significant value to The Geysers.
The USGS Regional Seismic Network is responsible for these fully functional items:

Seismic Data	
Acquisition	Six three-component USGS seismic stations contribute to seismicity determinations within The Geysers.
Processing	Seismic waveforms are intially compiled and p-wave arrival times calculated at the USGS "Waveserver"located within the Geysers Administration Center (and adjacent to the LBNL seismic data server).
Transfer	Merged LBNL/USGS station waveforms and arrival times are forwarded by a Northern California Seismic Network radio link to their Geysers Peak microwave hub, then transmitted to the USGS facility at Menlo Park.
Integration	LBNL/USGS P-wave arrival times are integrated with P-wave arrival times from other monitoring networks operated by the USGS, UC Berkeley, the California Geological Survey, and the California Department of Water Resources.
Analysis	Automatic determination of seismic event magnitude, hypocenter, first-motion mechanisms, and moment tensor solutions/shake maps (for seismic events with magnitude > 3.5). Seismologists complete reviews of more significant events.
Distribution	The USGS Eartquake Hazards Program website (https://earthquake.usgs.gov/) is the starting point for access to almost unlimited seismicty information, including nearly "real-time" availability of earthquake information (https://earthquake.usgs.gov/earthquakes/map/).
Archival	Waveforms and event determinations retrieved hourly for archival at the UC Berkeley Northern California Earthquake Data Catalog. Data derived from this catalog, including tomographic double-difference refined seismicty hypocenter determinations, contributes to Calpine/NCPA seismicity analysis, along with worldwide seismic research collaborations.



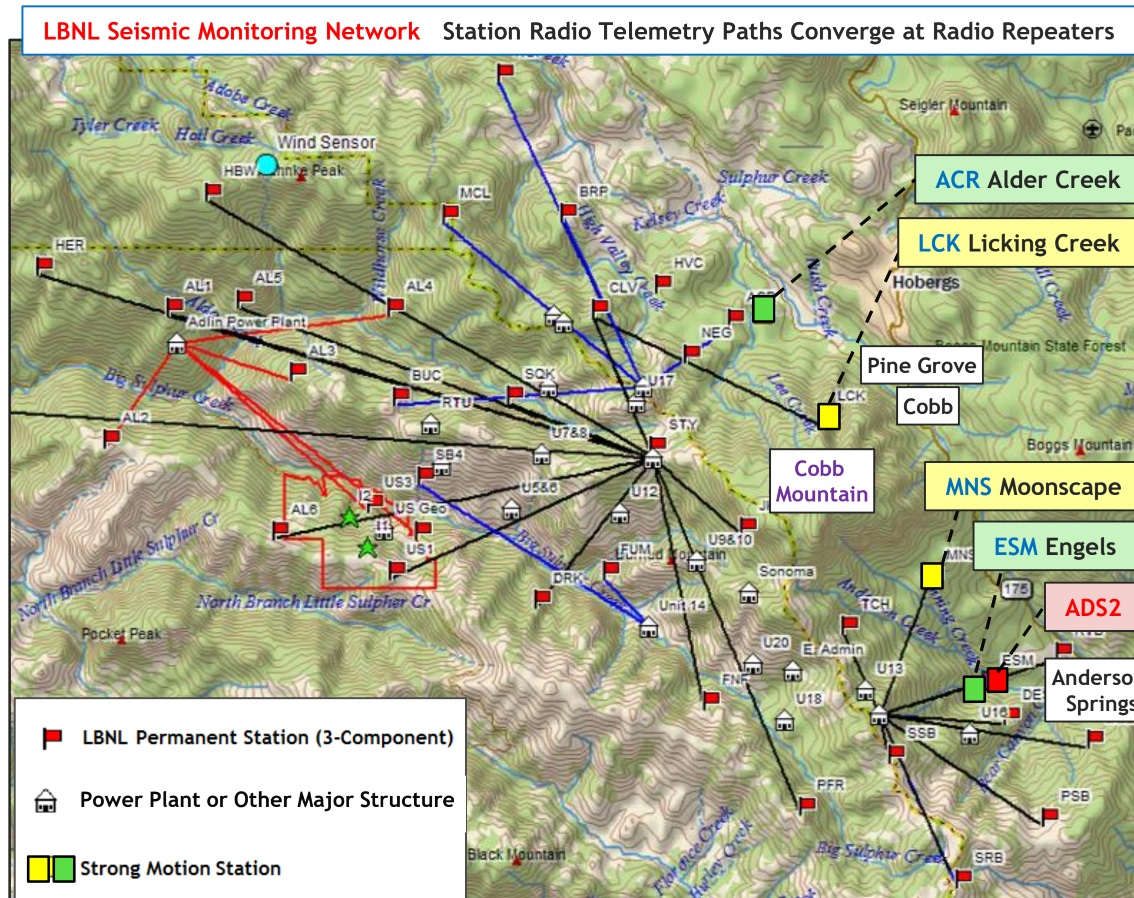


*** United States Geological Survey**

LBNL / Calpine Strong Motion Data Network

Calpine Corporation has purchased four Nanometrics Titan 3C accelerometers and cables:

Equipment: $4,800 per sensor station
Installation: $2,500 per sensor station
Total: $7,300 per sensor station



Now integrated with existing LBNL seismic monitoring network:

ESM Engels Strong Motion - Anderson Springs
ACR Alder Creek – Cobb Area

Soon integrated with existing LBNL seismic monitoring network:

LCK Licking Creek
MNS Moonscape
Q4 2019 installation delayed by Kincade Fire

These stations provide the following significant upgrades for improved strong motion data accuracy and reliability:

Nanometrics Titan 3C Accelerometers
Solar Power
Radio Telemetry

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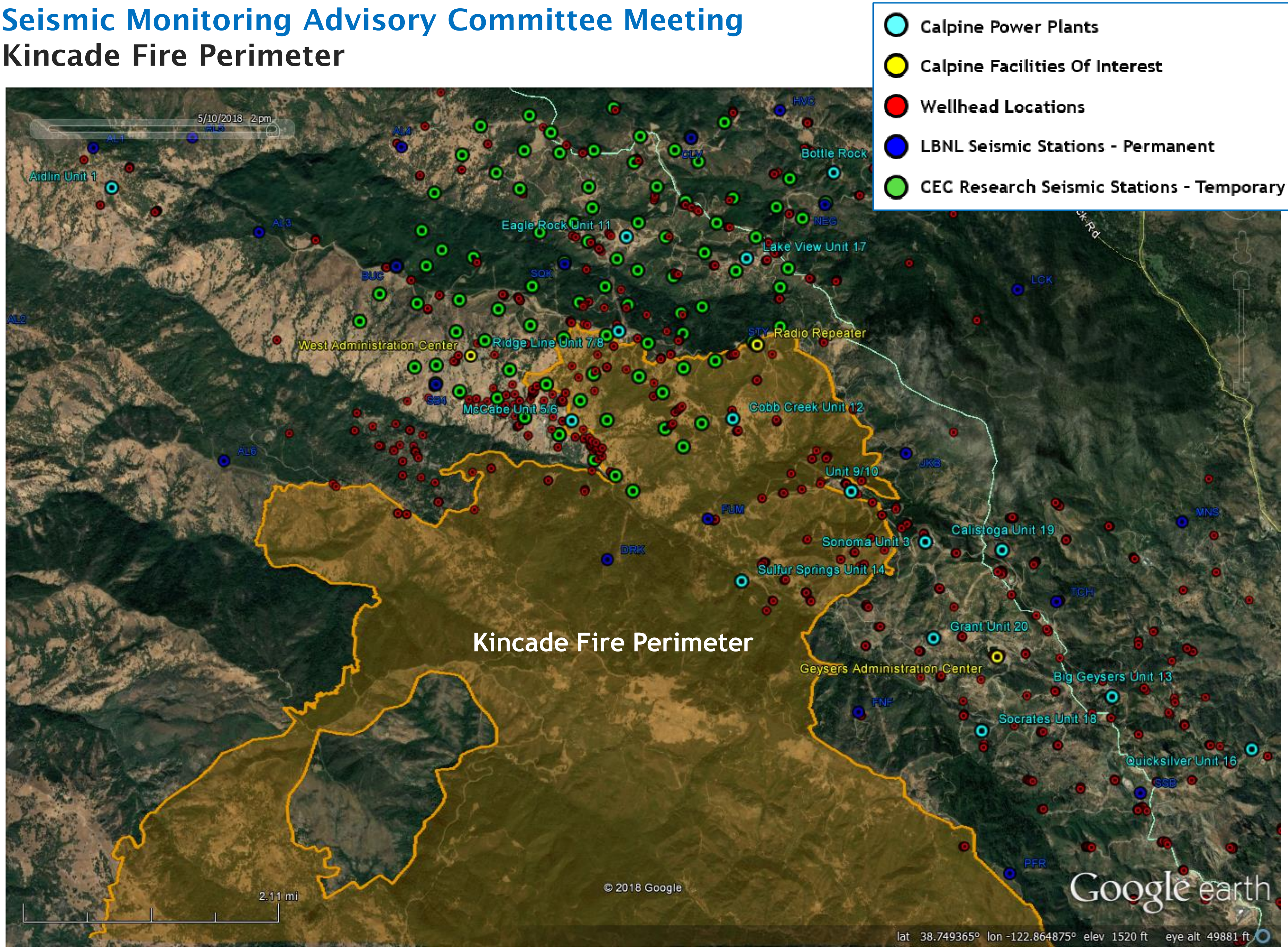
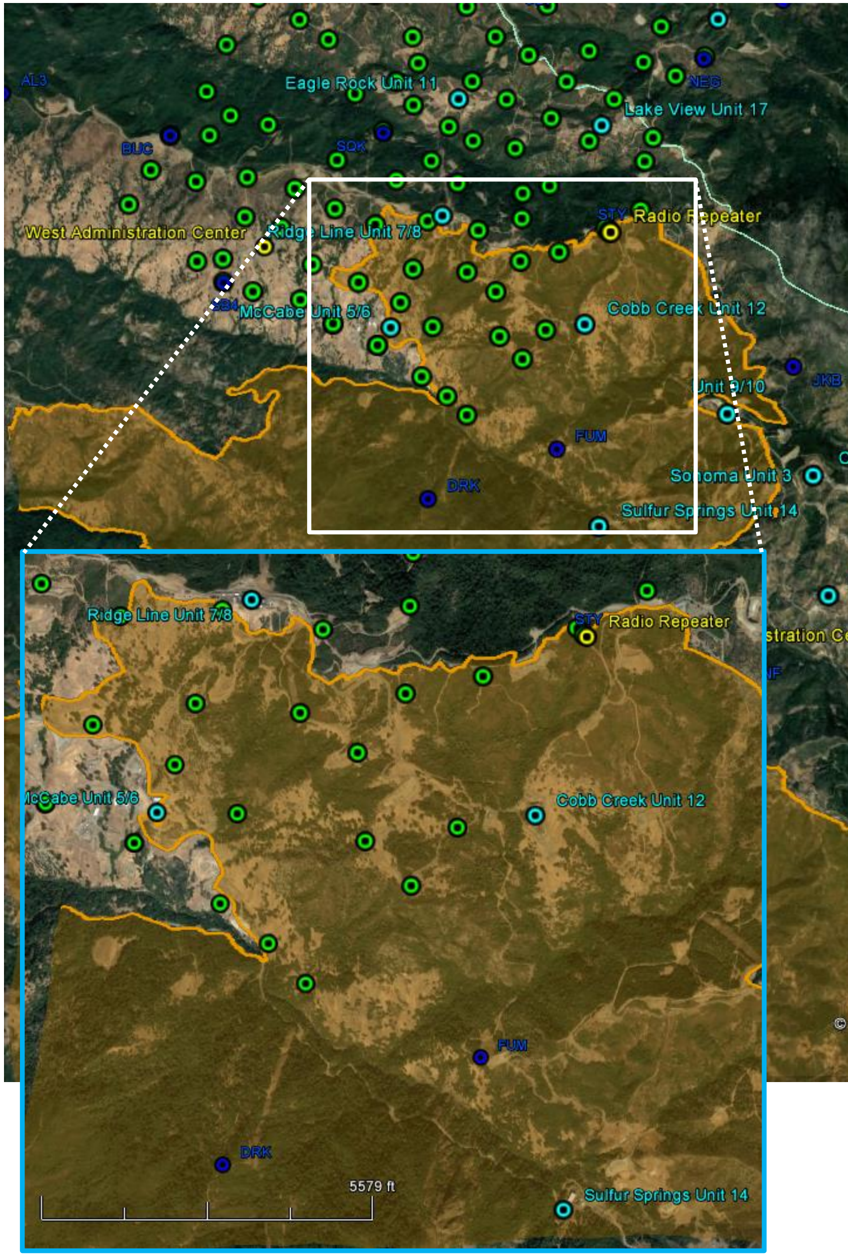
Kincade Fire Perimeter



Kincade Fire



- The Kincade Fire significantly impacted central Geysers power and communications.
- Fieldwide water injection and steam production initially “shut-in”.

- **LBNL Seismic Monitoring Network**
- 3 of 34 stations within Kincade Fire Perimeter
- DRK, FUM, STY
- 4 of 34 stations close to KF perimeter
- PFR, JKB , FNF, SSR/SRB
- DX Radio Repeater within Kincade Fire Perimeter

- **CEC Funded High-Resolution Seismic Network**
- 20 of 93 temporary seismic stations were within or very near the fire perimeter.

- **Conclusions**
- Station STY fire-damaged; repairs required.
- Communication loss for all stations with data flow through the DX radio repeater site (east of DX 24 well pad; near STY).
- Relocated LBNL server to DX radio repeater site. (generator on-site for power)
- Initiated data card swaps at 16 stations in danger of data loss.

- All CEC high-resolution stations survived fire as they were:

1) sited in areas of limited vegetation for better solar exposure, and
2) placed on rock outcrops for better coupling.

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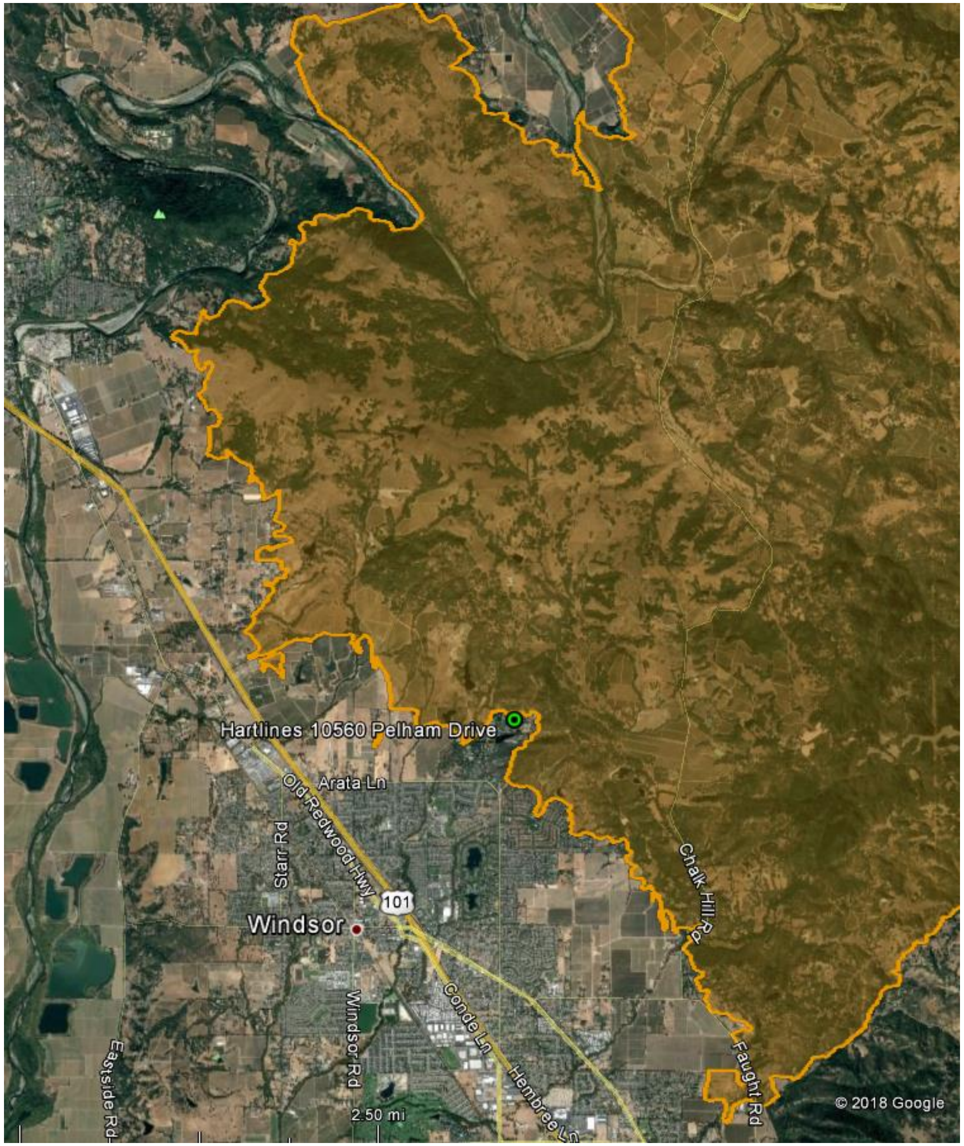
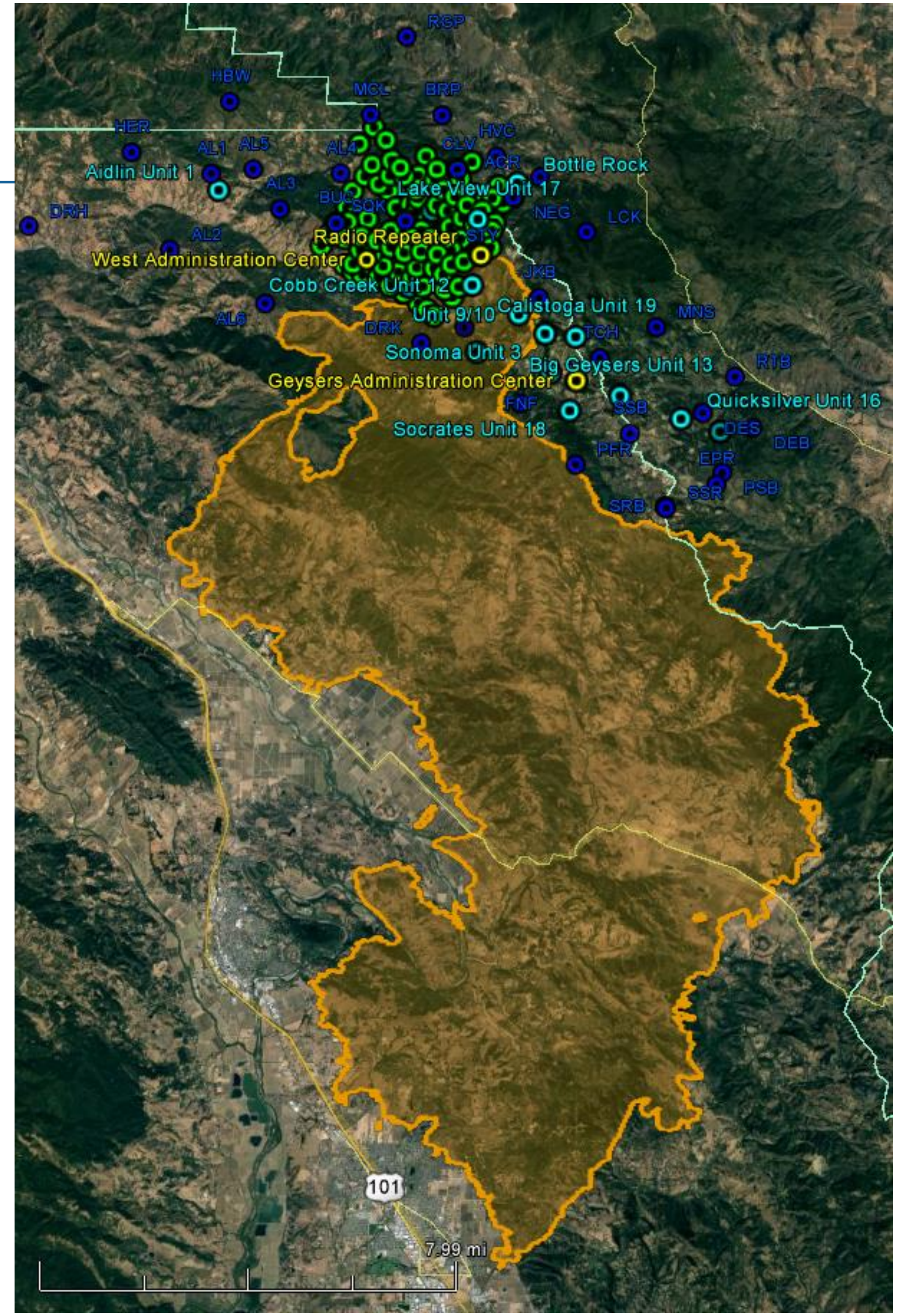
Kincade Fire Perimeter





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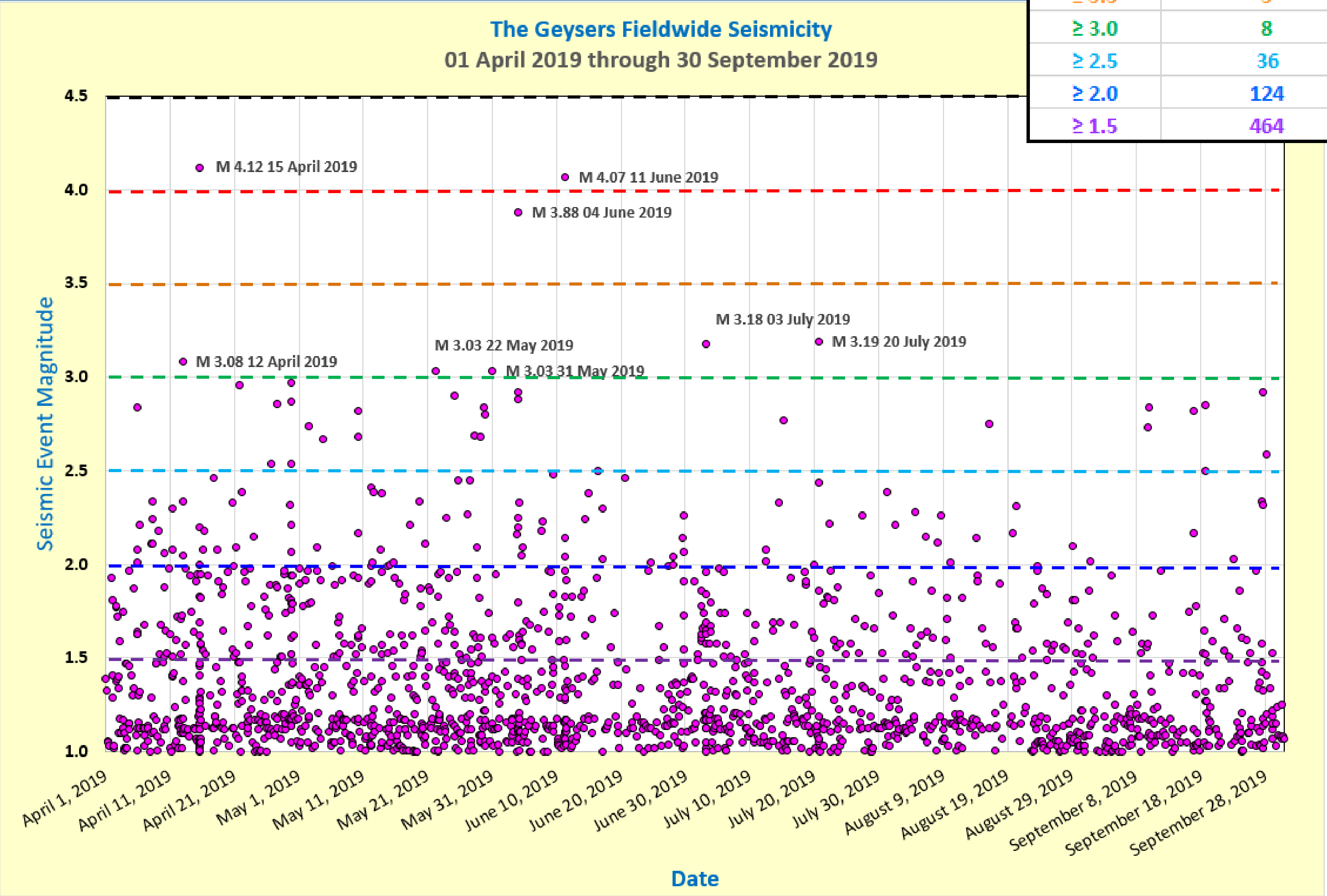
Field-wide Seismicity Analysis

01 April 2019 to 30 September 2019

Magnitude	Number of Events
≥ 4.5	0
≥ 4.0	2
≥ 3.5	3
≥ 3.0	8
≥ 2.5	36
≥ 2.0	124
≥ 1.5	464



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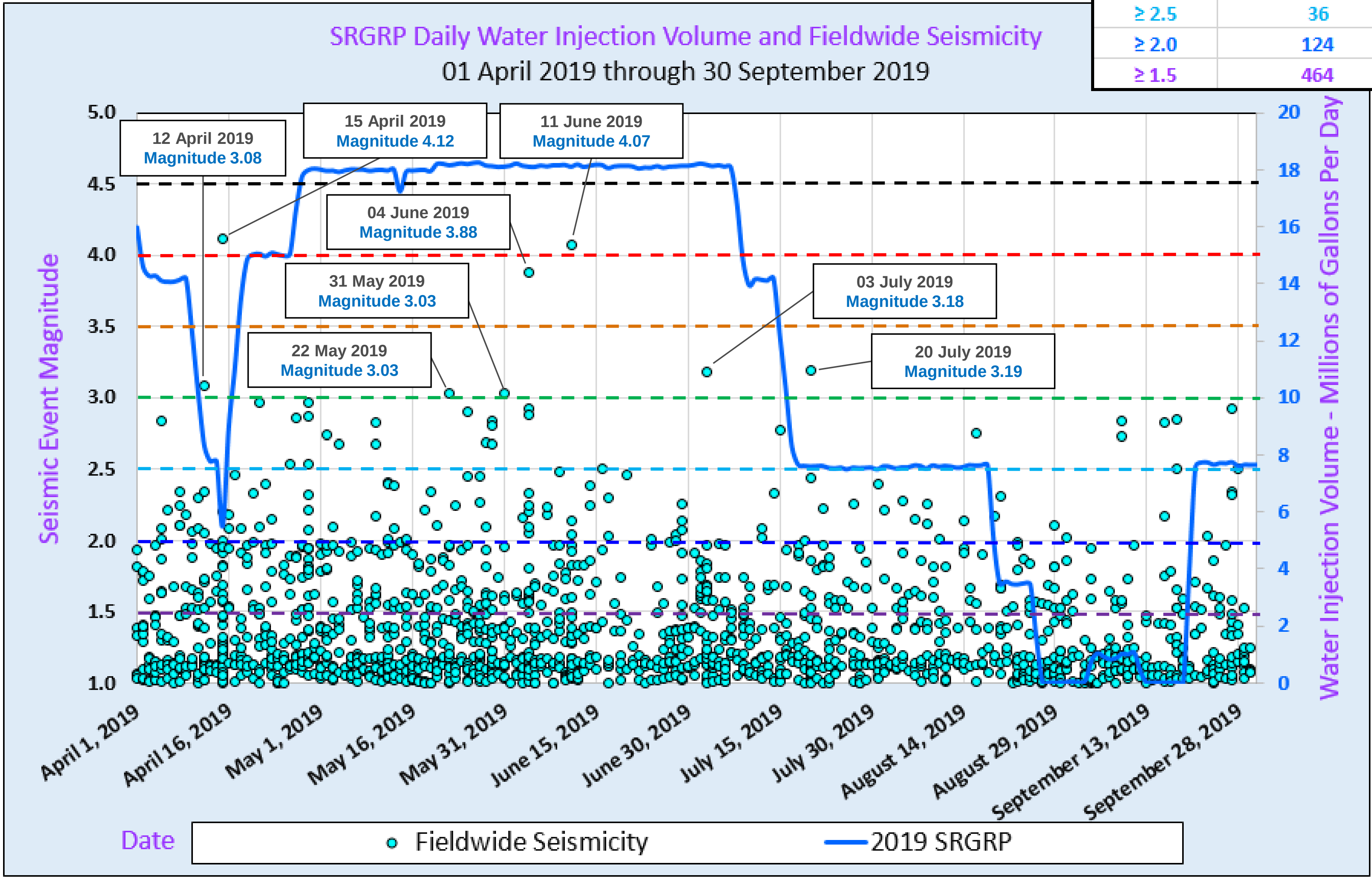
Santa Rosa Geysers Recharge Project

Daily Water Injection Volume and Fieldwide Seismicity

Magnitude	Number of Events
≥ 4.5	0
≥ 4.0	2
≥ 3.5	3
≥ 3.0	8
≥ 2.5	36
≥ 2.0	124
≥ 1.5	464



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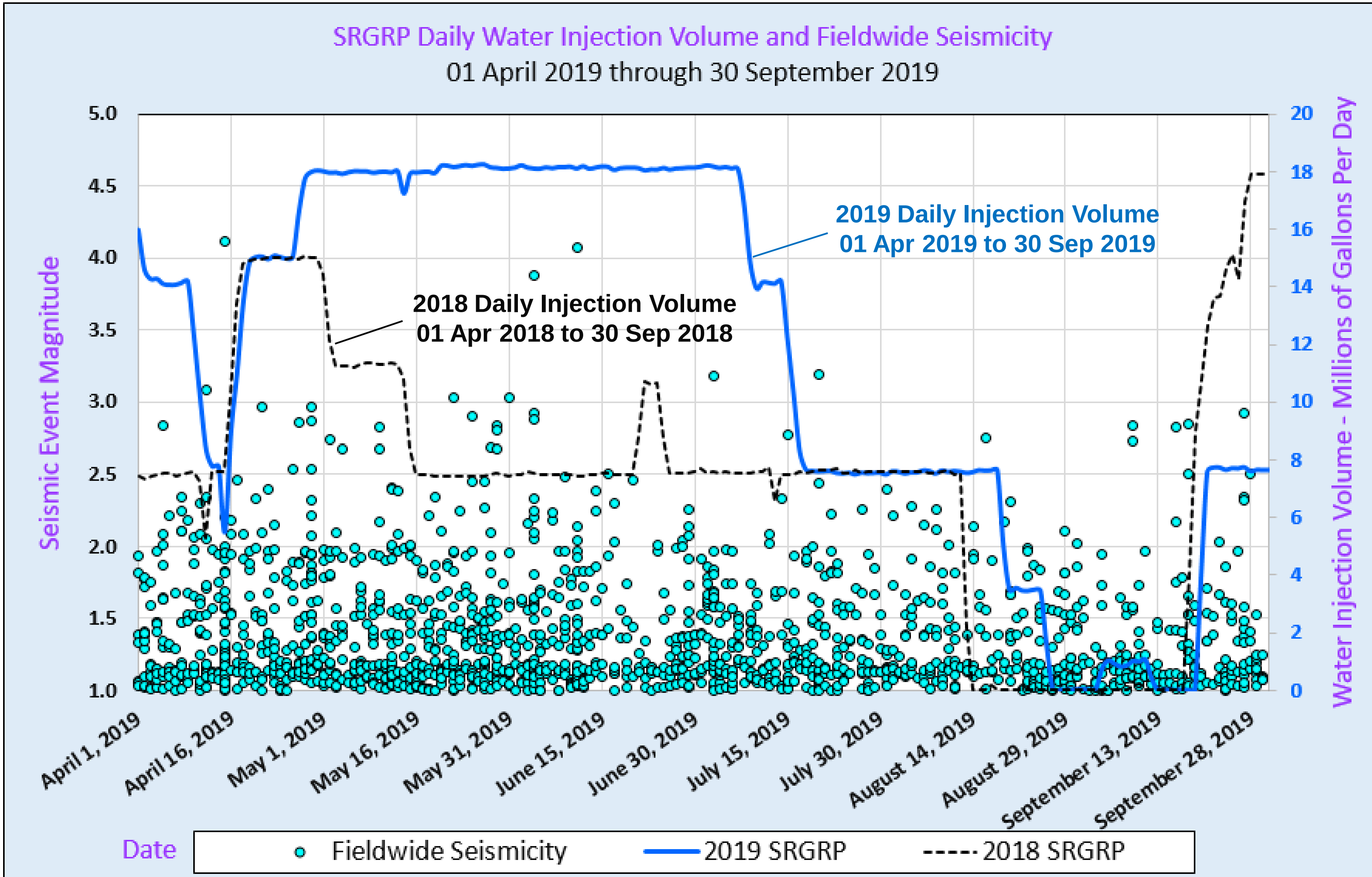
Santa Rosa Geysers Recharge Project

Daily Water Injection Volume and Fieldwide Seismicity



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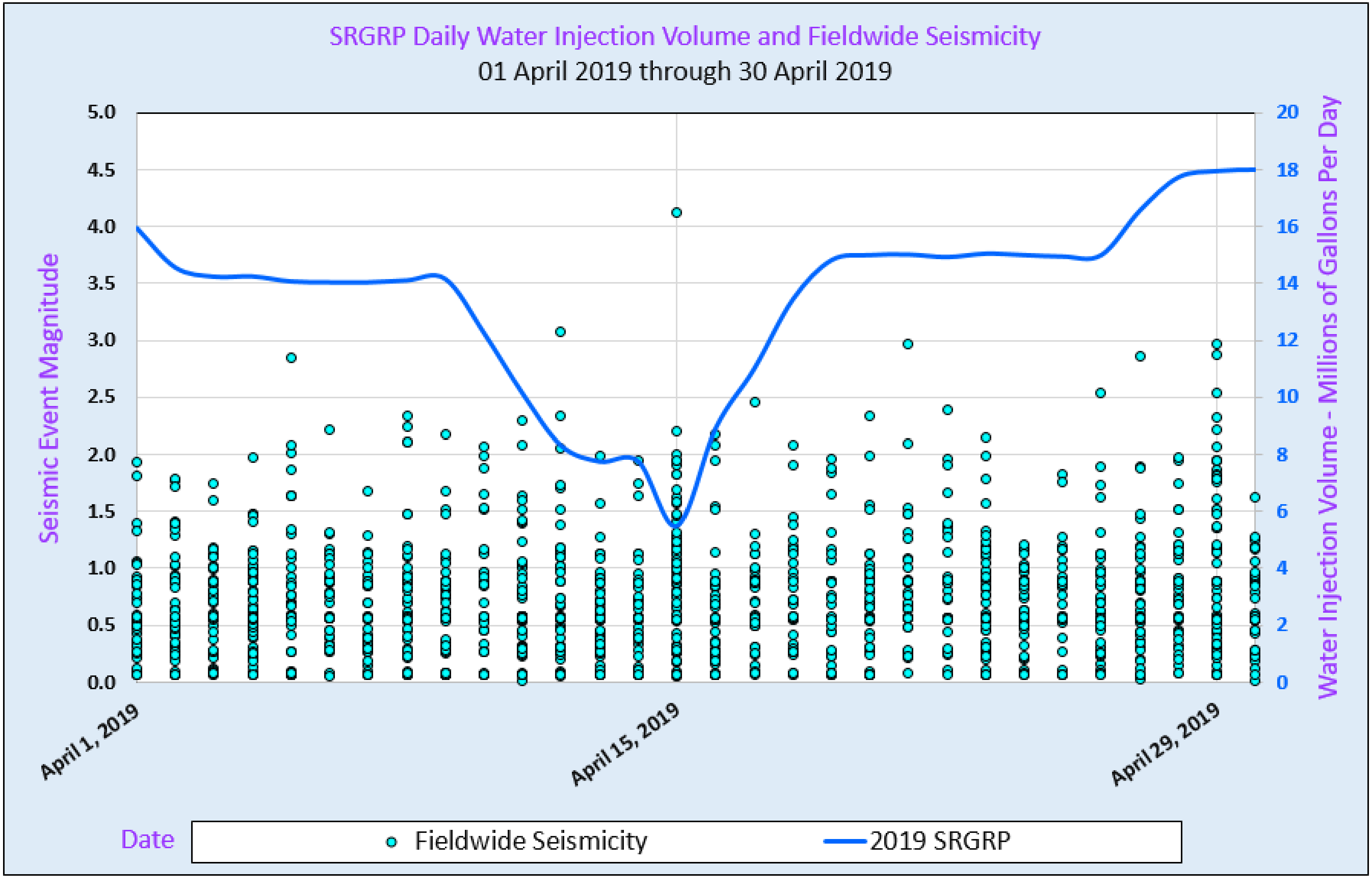
Santa Rosa Geysers Recharge Project

April 2019 Daily Water Injection Volume and Fieldwide Seismicity



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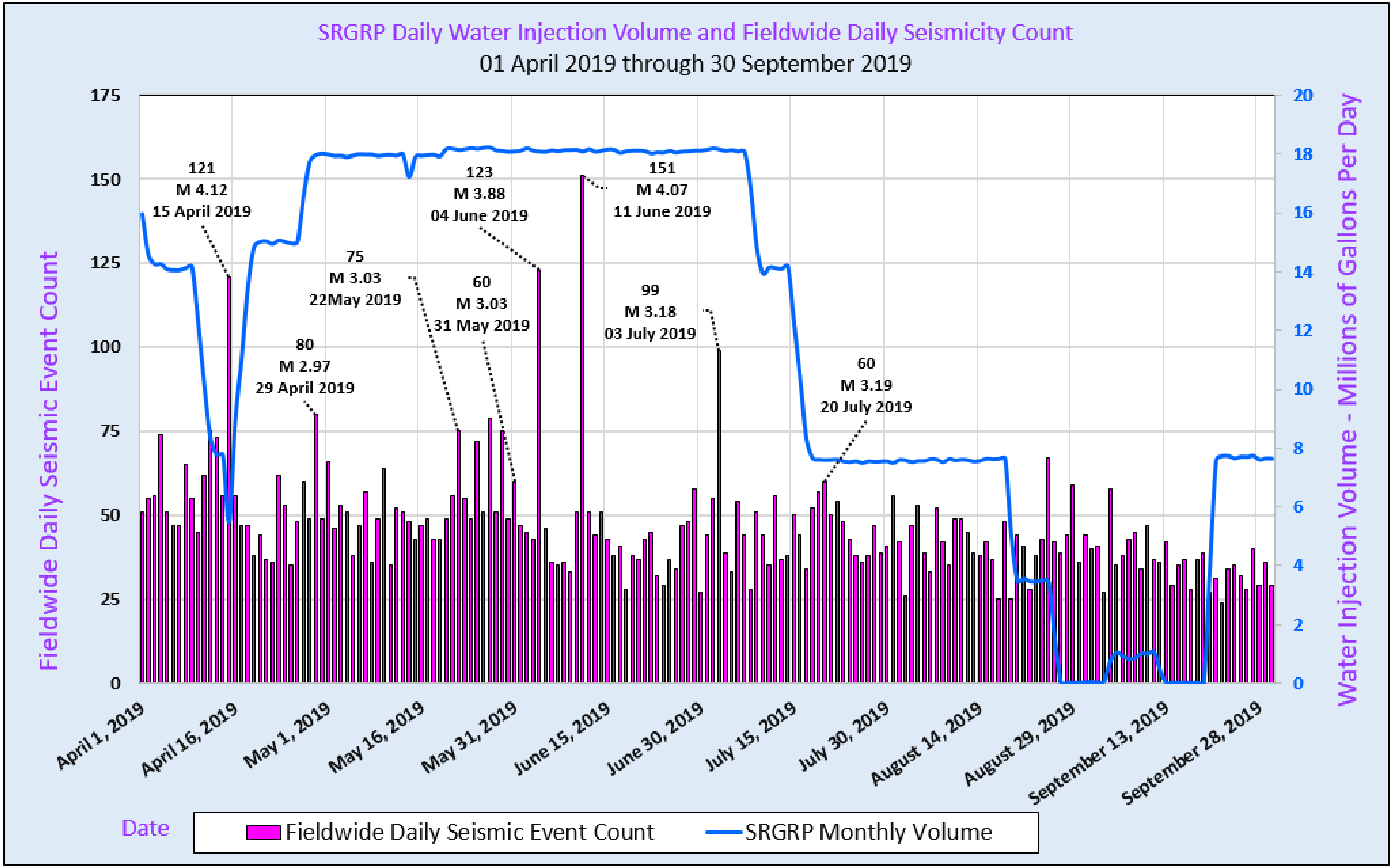
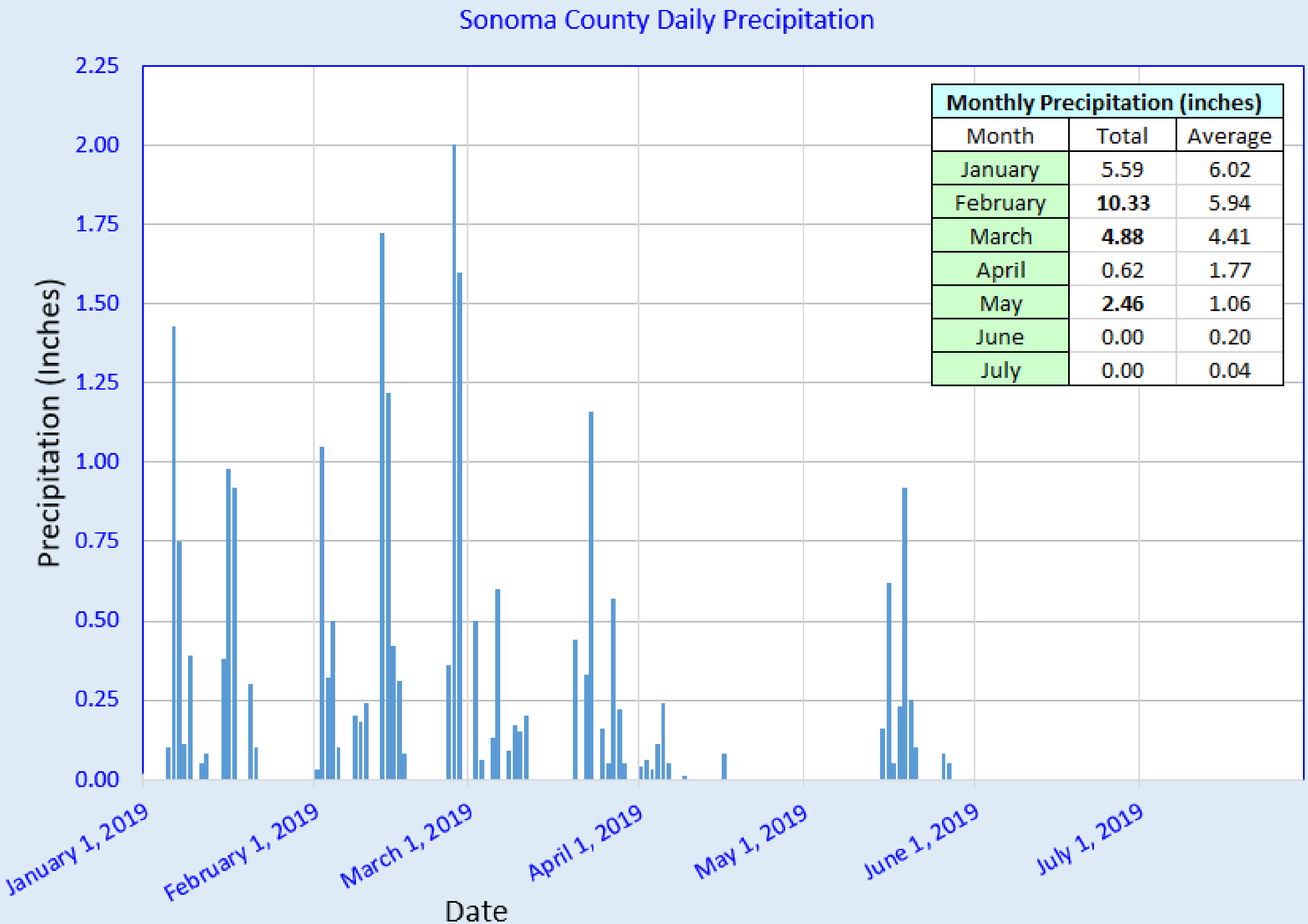
Santa Rosa Geysers Recharge Project

Daily Water Injection Volume and Fieldwide Daily Seismicity Count



Sonoma County Daily Precipitation
01 January Through 31 July 2019



Monthly Precipitation (inches)		
Month	Total	Average
January	5.59	6.02
February	**10.33**	5.94
March	**4.88**	4.41
April	0.62	1.77
May	**2.46**	1.06
June	0.00	0.20
July	0.00	0.04

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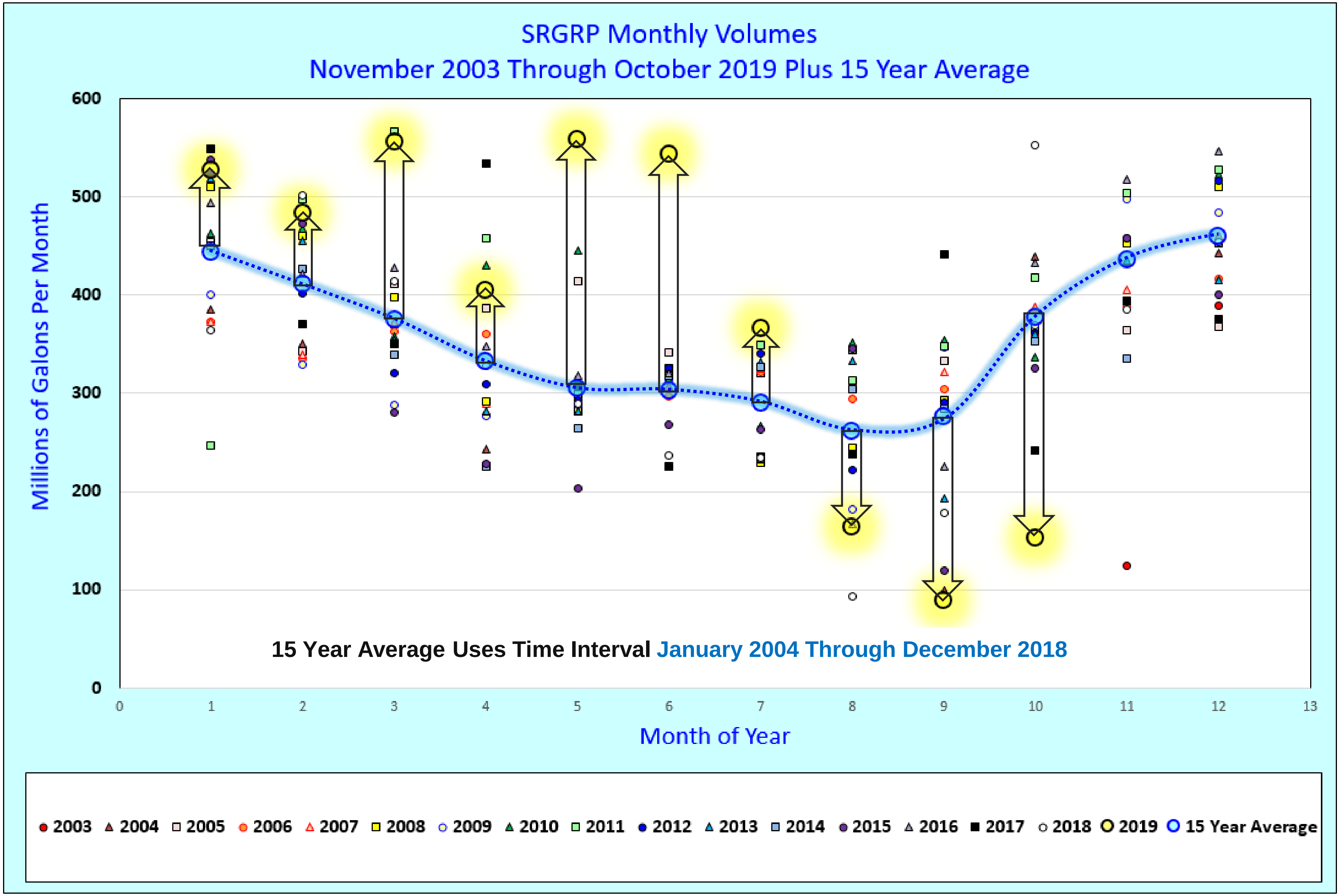
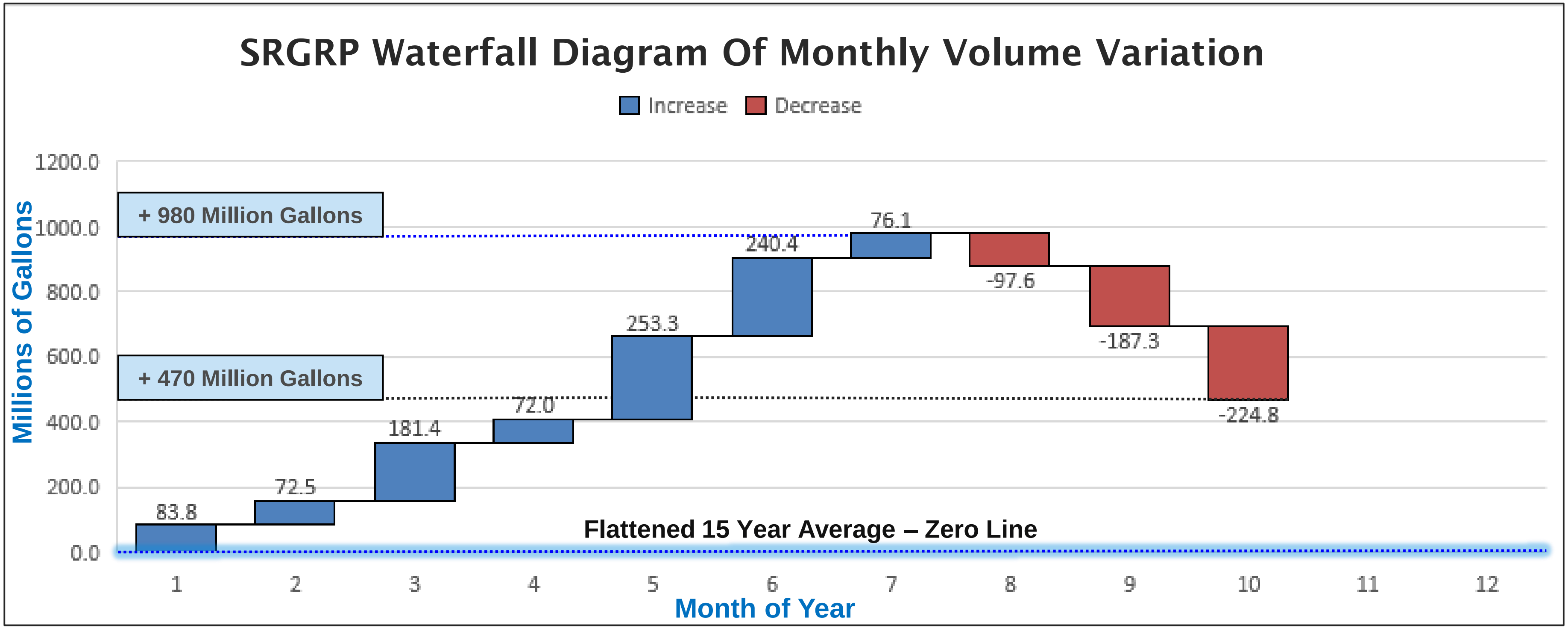
SRGRP Water Injection Monthly Volumes Beginning November 2003



SRGRP Monthly Volume Variation
Referenced To "Flattened" Average Monthly Volume At Zero Line



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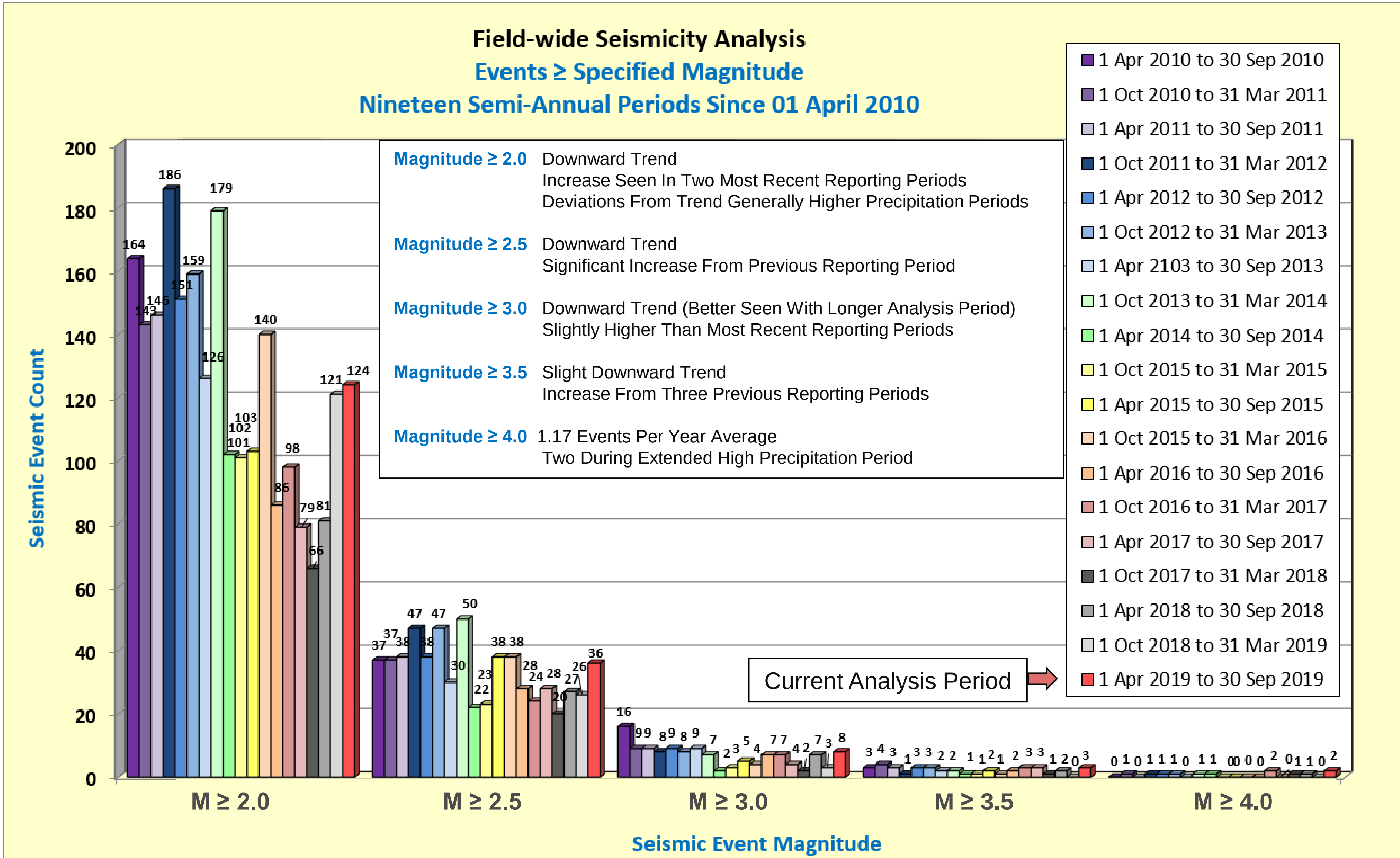
Field-wide Seismicity Analysis

Comparison of Eighteen Semi-annual Reporting Periods



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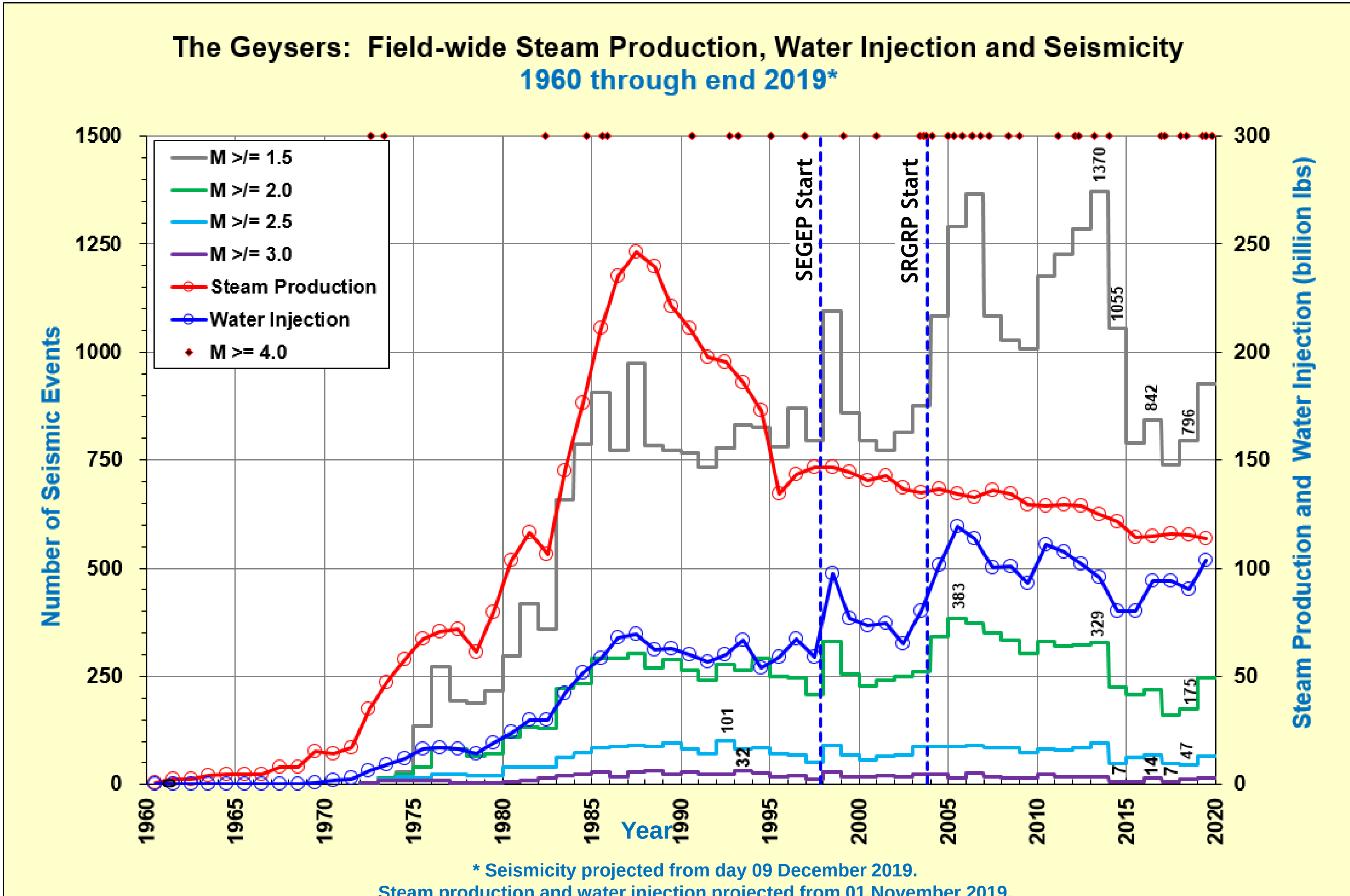
Yearly Field-wide Steam Production, Water Injection and Seismicity



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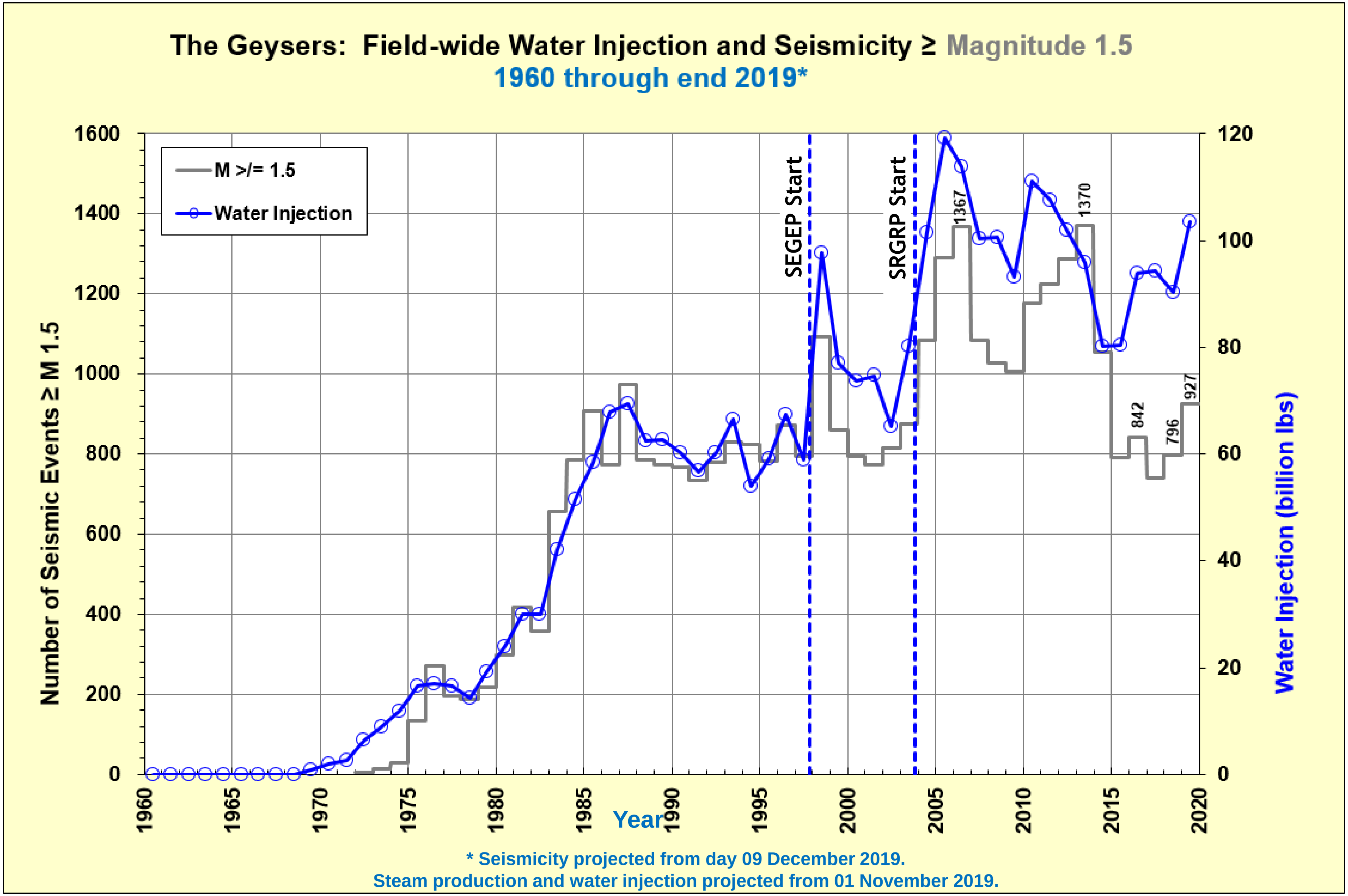
Yearly Field-wide Water Injection and Seismicity ≥ Magnitude 1.5



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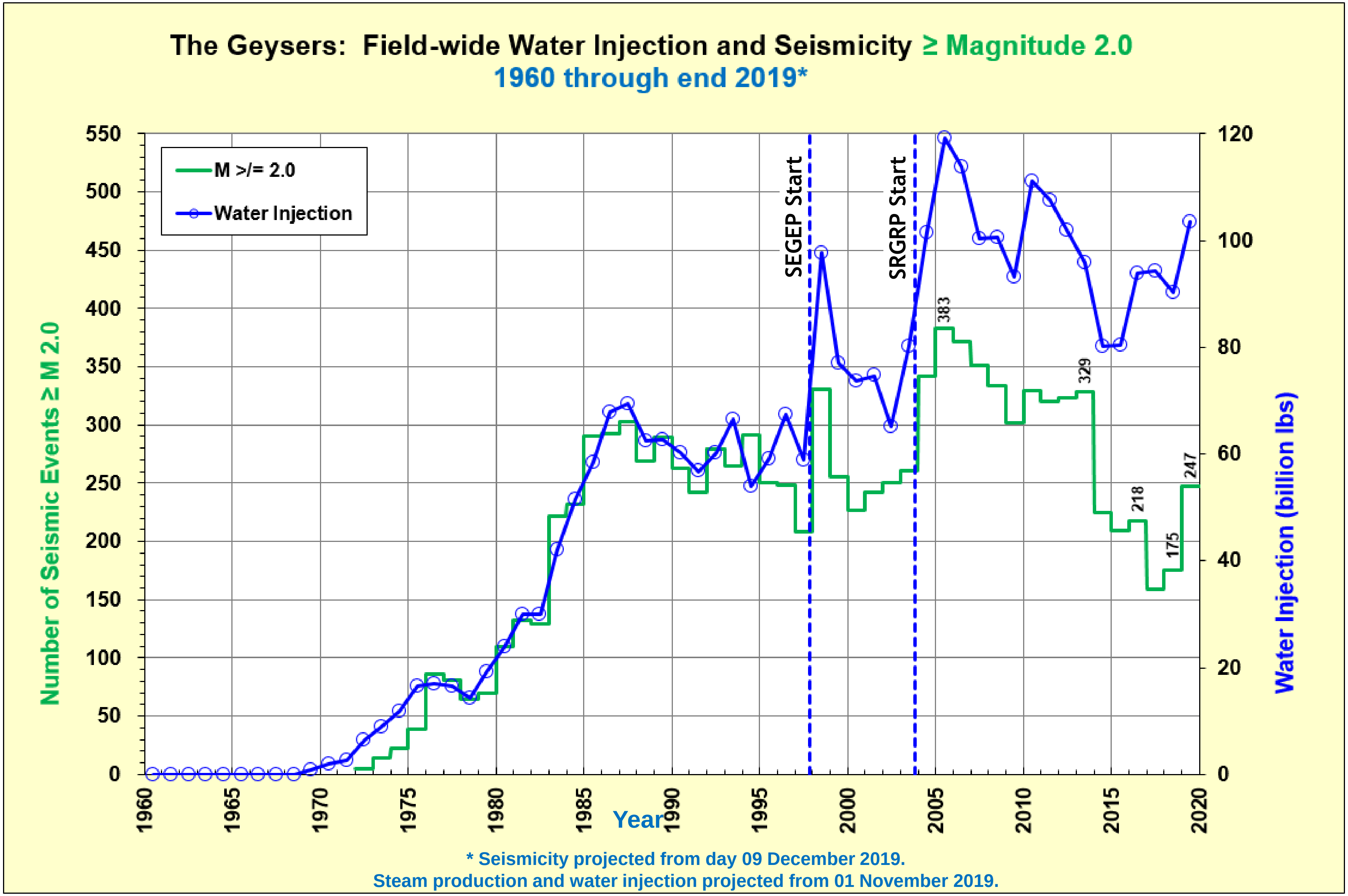
Yearly Field-wide Water Injection and Seismicity ≥ Magnitude 2.0



* Seismicity projected from day 09 December 2019.
Steam production and water injection projected from 01 November 2019.

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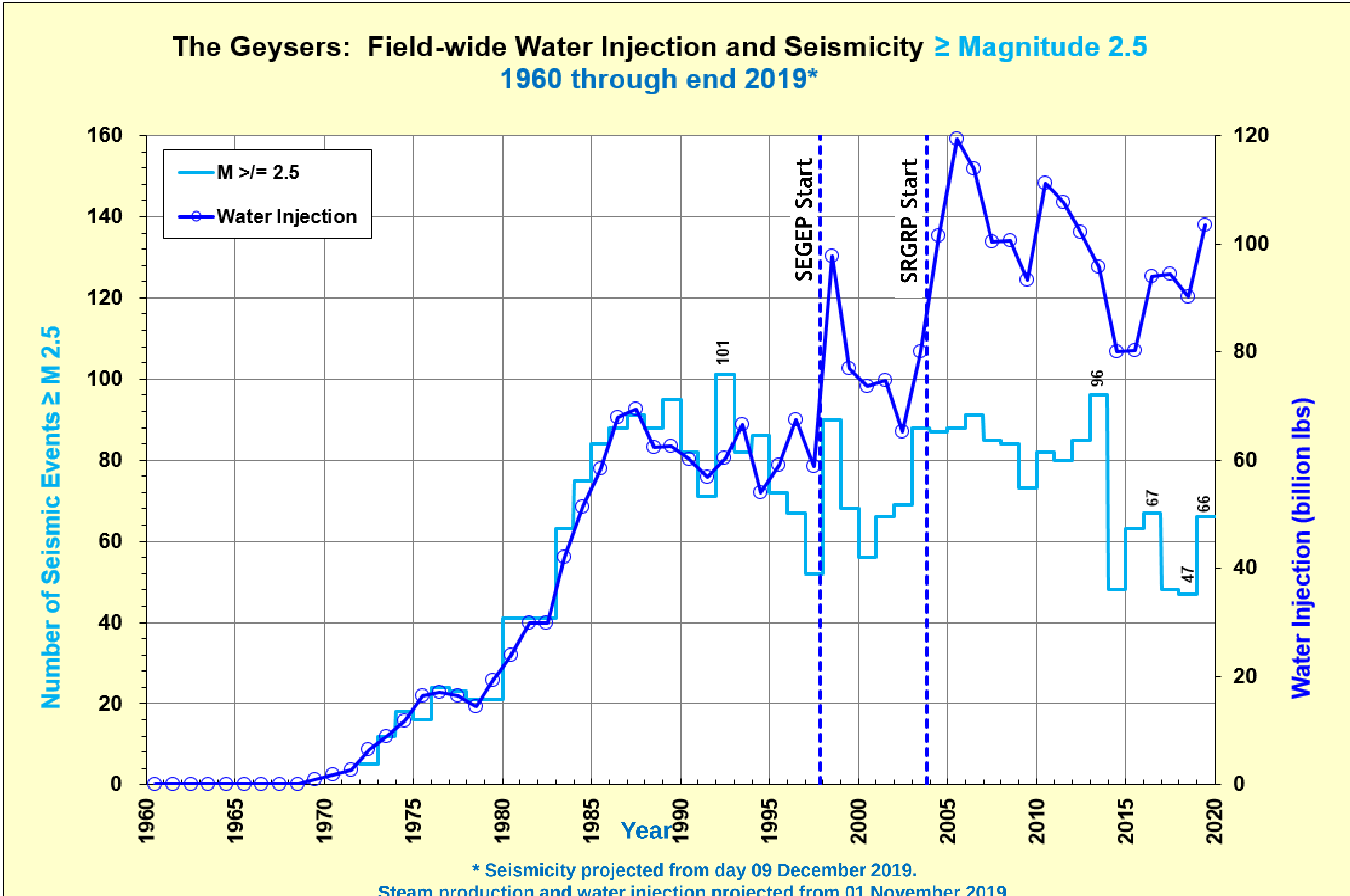
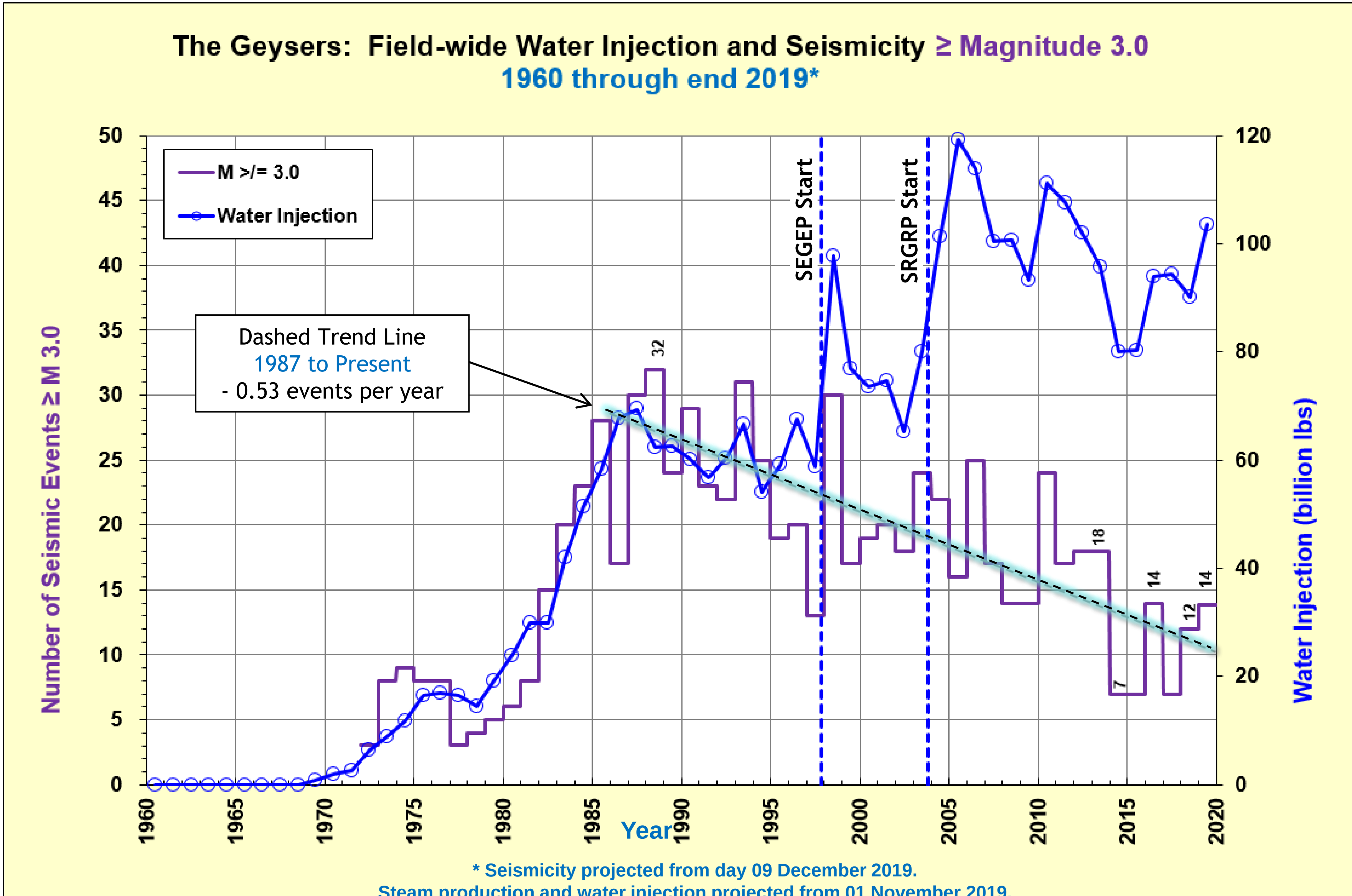
Yearly Field-wide Water Injection and Seismicity ≥ Magnitude 2.5



Yearly Field-wide Water Injection and Seismicity ≥ Magnitude 3.0



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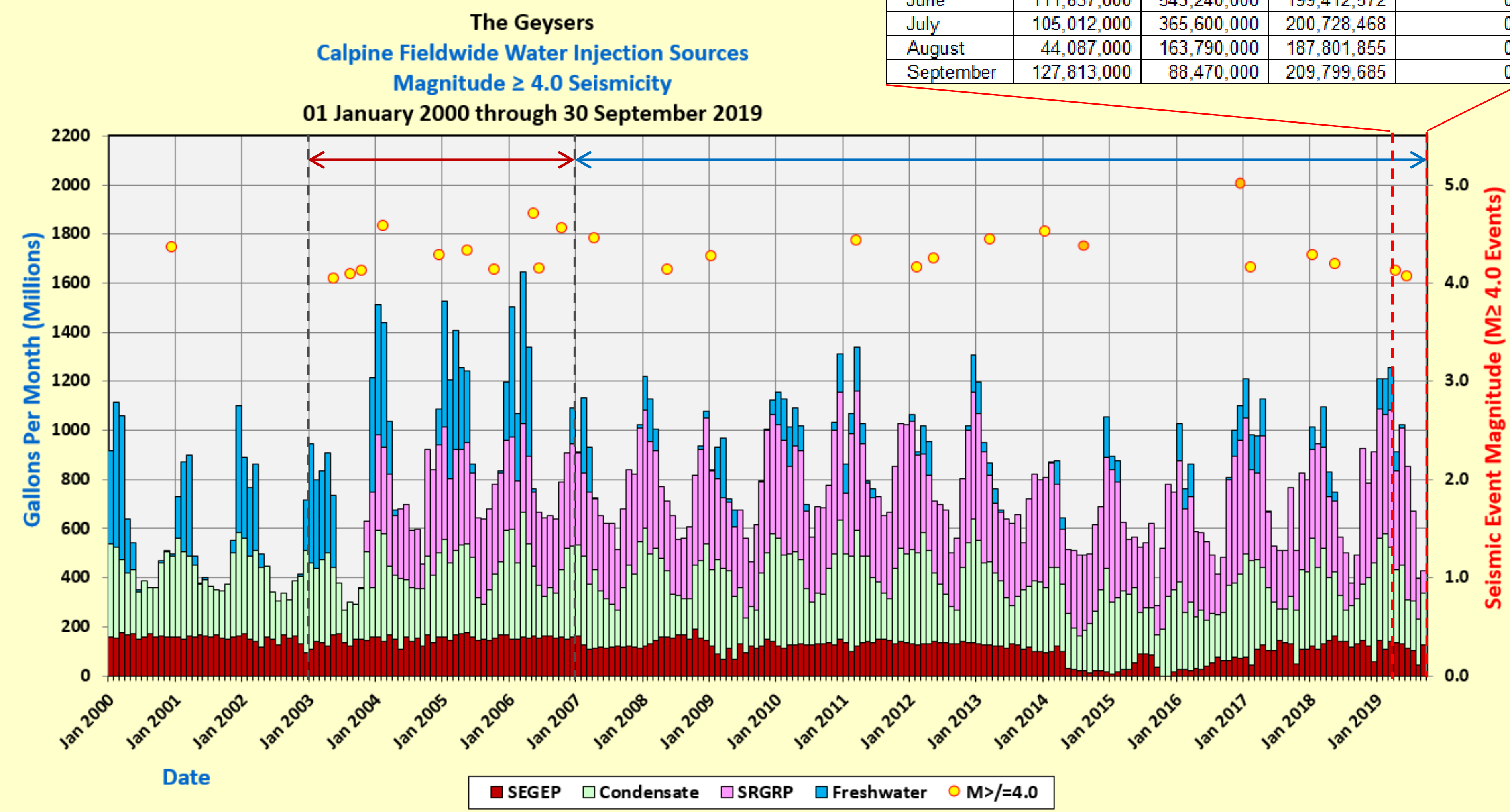
Monthly Field-wide Water Injection By Source vs. Magnitude ≥ 4.0 Seismicity

Average Number of Magnitude ≥ 4.0 Events Since January 2007 is 1.17 Per Year

Time Period	Magnitude ≥ 4.0 Seismic Events
January 2003 through December 2006	2.50 per year
January 2007 through September 2019	1.17 per year

Water Supply for Reporting Period (Six Months)

Water Injection Sources (Gallons)				
Month	SEGEP	SRGRP	Condensate	Fresh Water
April	136,614,000	404,770,000	295,214,398	77,509,211
May	129,314,000	558,440,000	321,843,556	11,931,987
June	111,837,000	543,240,000	199,412,572	0
July	105,012,000	365,600,000	200,728,468	0
August	44,087,000	163,790,000	187,801,855	0
September	127,813,000	88,470,000	209,799,685	0



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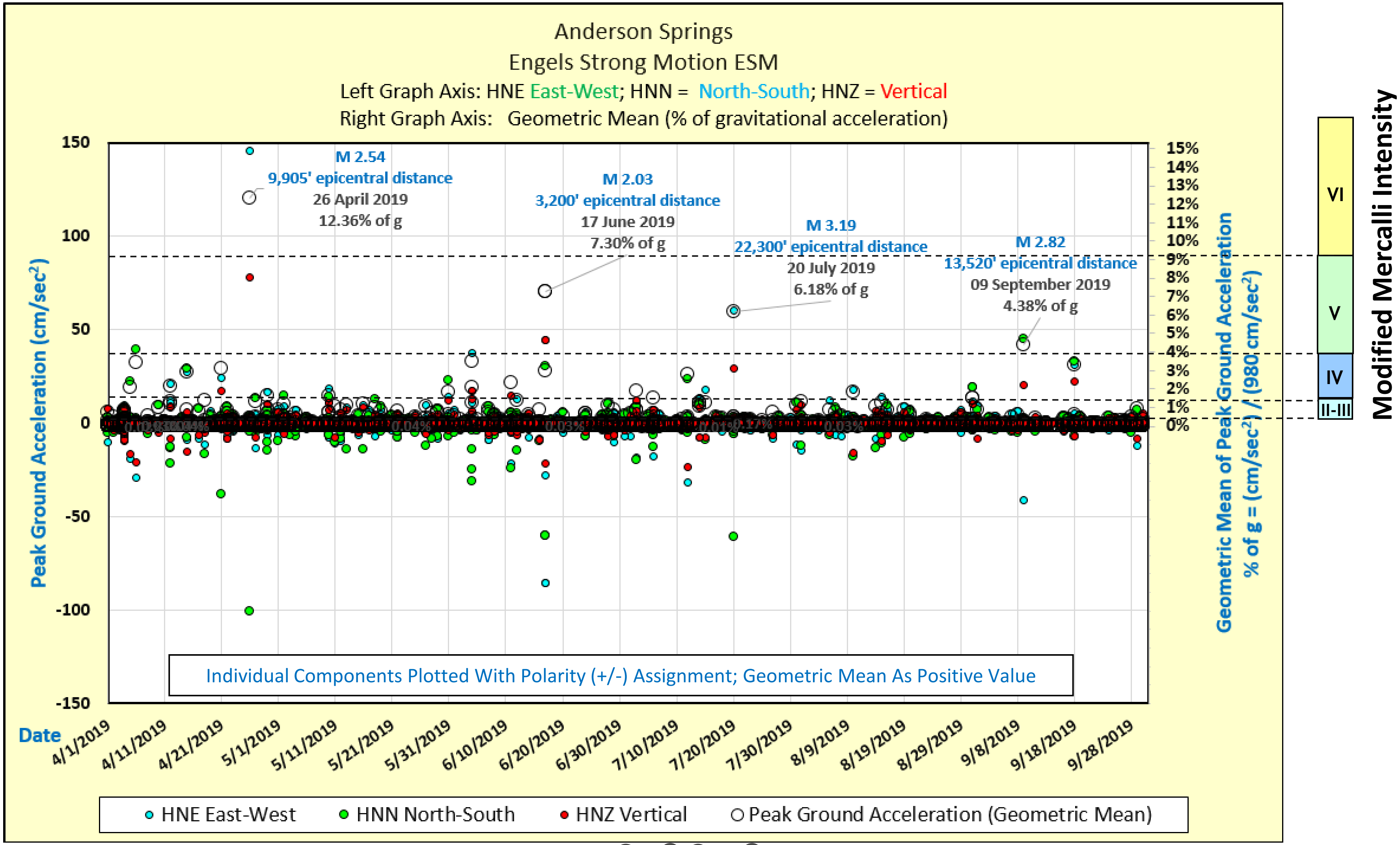
Anderson Springs Engels Strong Motion ESM



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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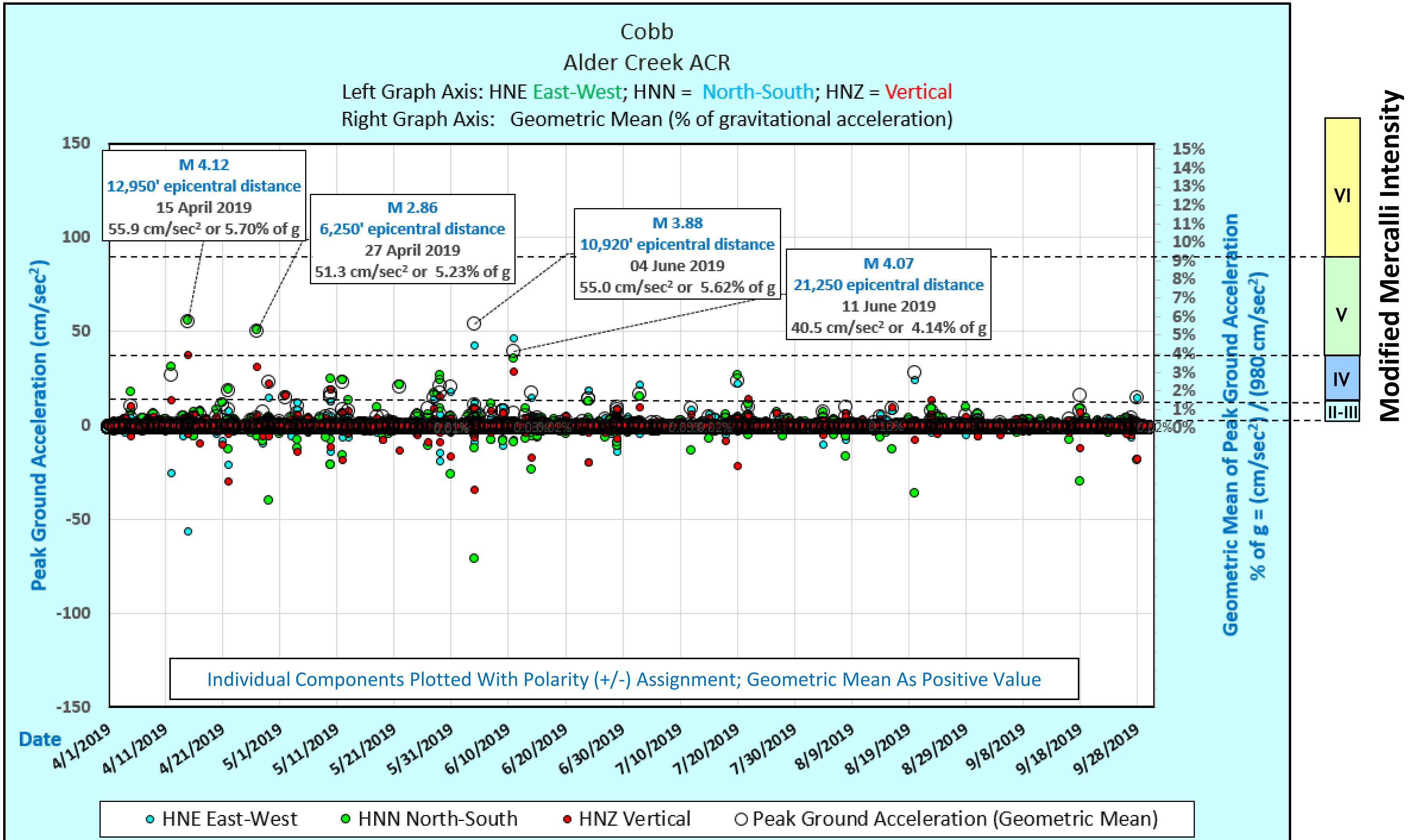
Cobb Alder Creek Strong Motion ACR



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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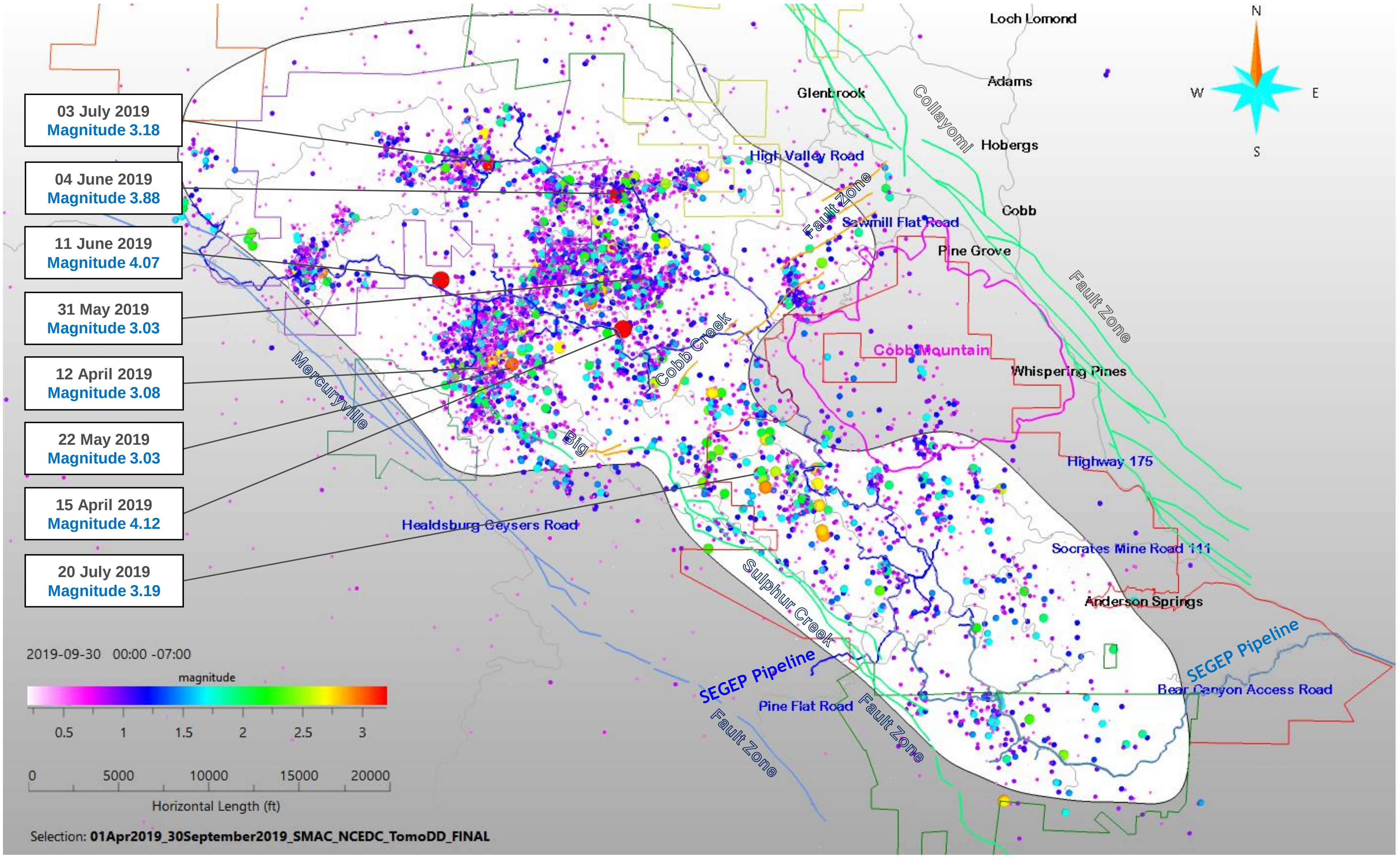
Field-wide Seismicity Animation

Seismic Events Color Scaled By Magnitude



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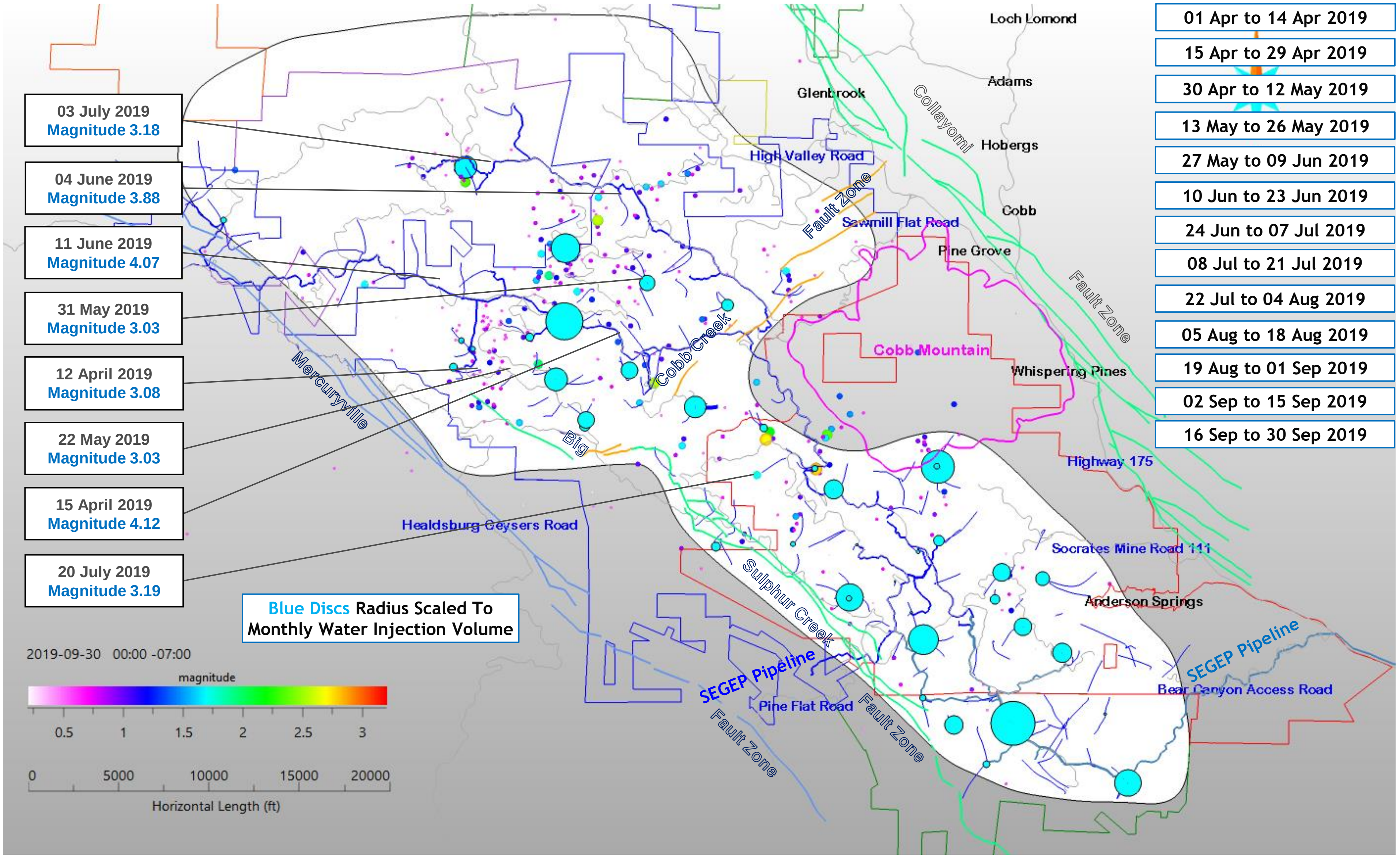
Field-wide Two Week Interval Water Injection and Seismicity Animation

Seismic Events Color Scaled By Magnitude



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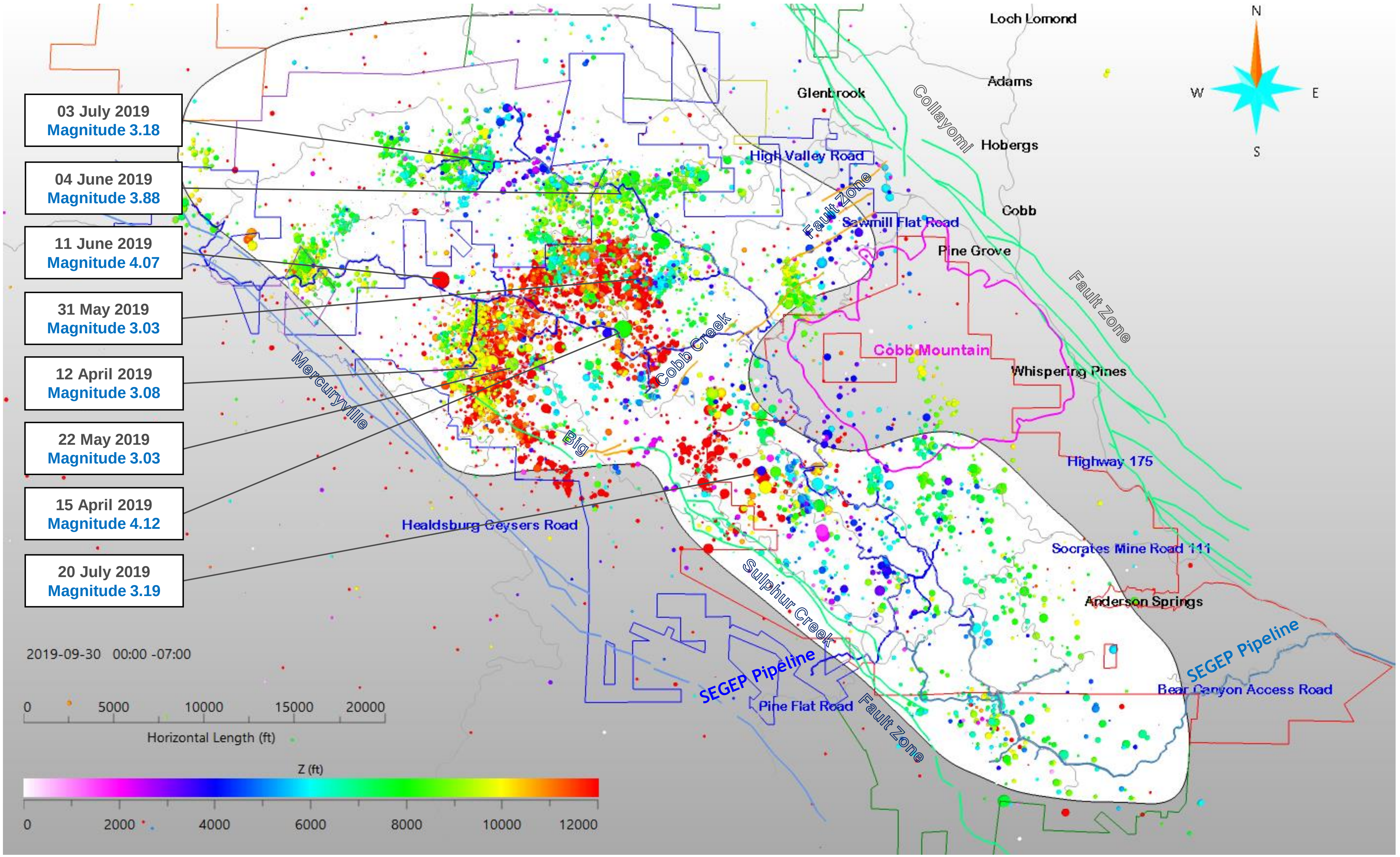
Field-wide Seismicity Animation
Seismic Events Color Scaled By Depth



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Calpine Community Hotline

A more active six month interval for seismicity, plus encouragement from Calpine to utilize the community hotline, resulted in a total of 29 calls to the Calpine Community Hotline during the current reporting period of 01 April 2019 to 30 September 2019.

The five seismic events of primary concern were:

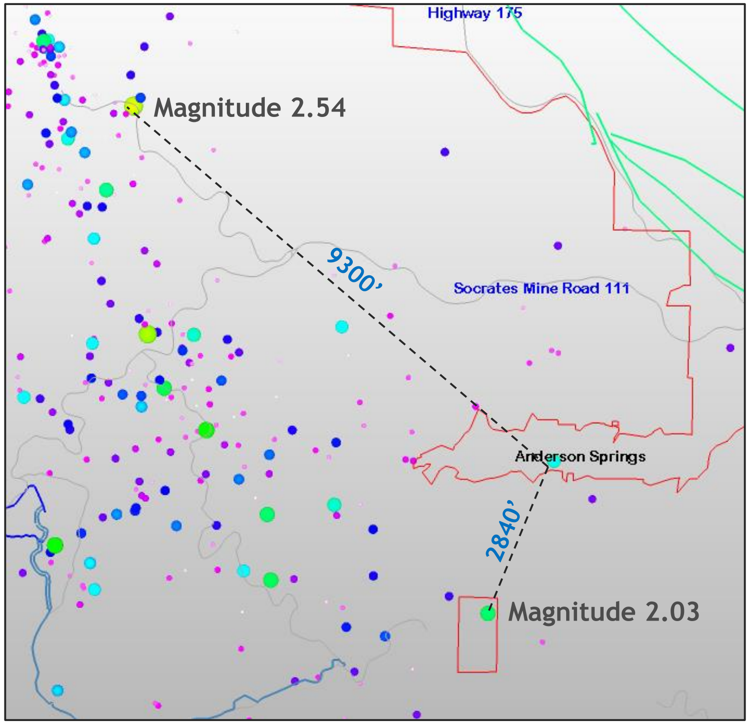
26 April 2019 Magnitude 2.54 at 14:40:20 UTC
9,300' Northwest of Anderson Springs 4 calls

04 June 2019 Magnitude 3.88 at 01:44:21 UTC
36,100' Northwest of Anderson Springs 5 calls
10,550' West of Cobb 2 calls

11 June 2019 Magnitude 4.07 at 07:46:25 UTC
42,200' Northwest of Anderson Springs 2 calls
21,500' West of Cobb 2 calls

17 June 2019 Magnitude 2.03 at 01:26:00
2,840' South-Southeast of Anderson Springs 5 calls

20 July 2019 Magnitude 3.19 at 15:57:53 UTC
21,500' West-Northwest of Anderson Springs 5 calls
15,800' South-Southwest of Cobb 1 call



Nine calls concerning two relatively low magnitude seismic events and limited epicentral distances. (energy *and* distance are important criteria)

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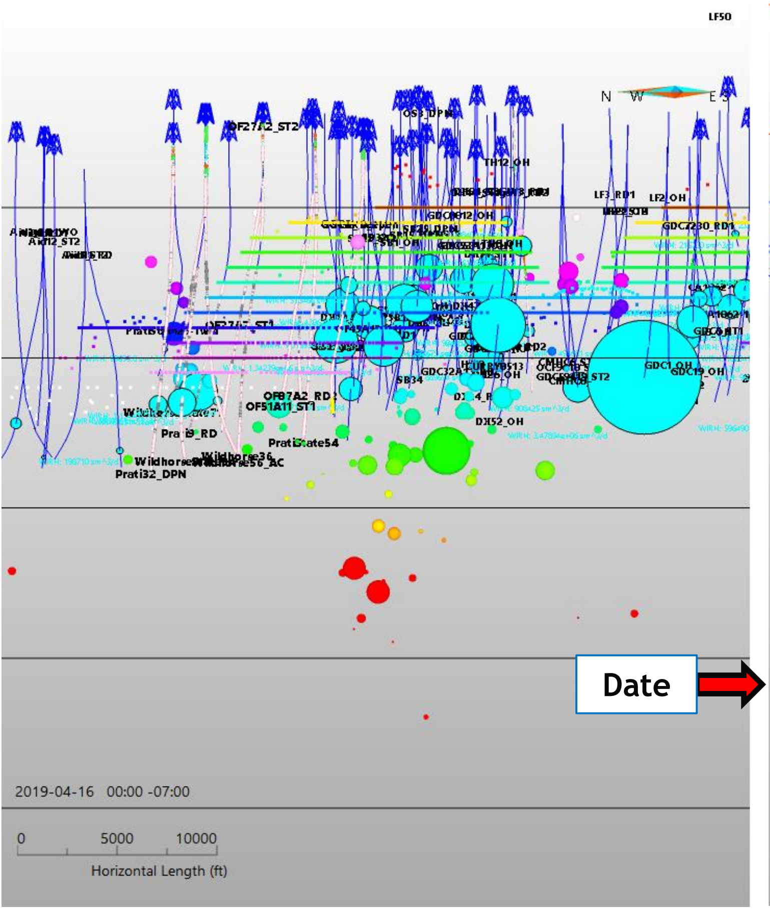
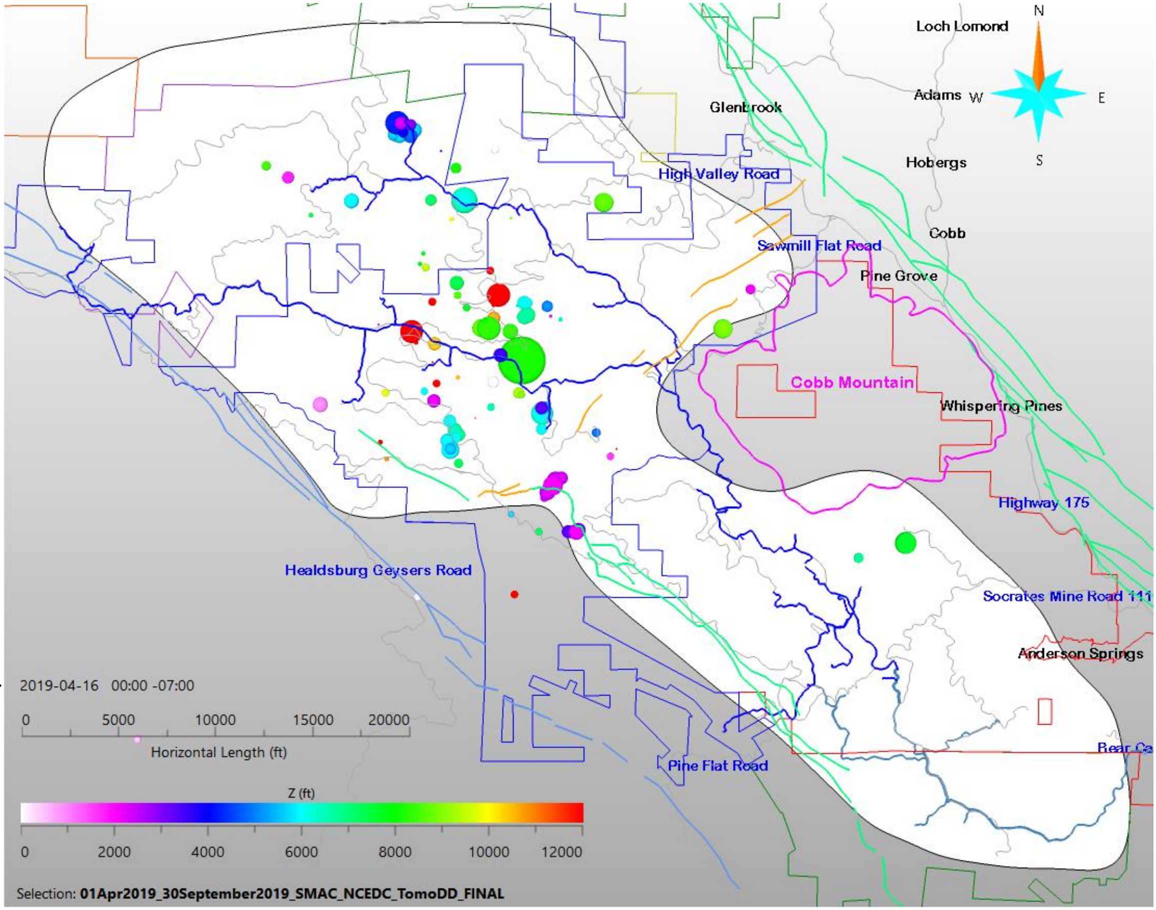
Daily Interval Seismicity Animation For April 2019

Seismicity Analysis At Limited Time Intervals
Days, Hours or Minutes



Date



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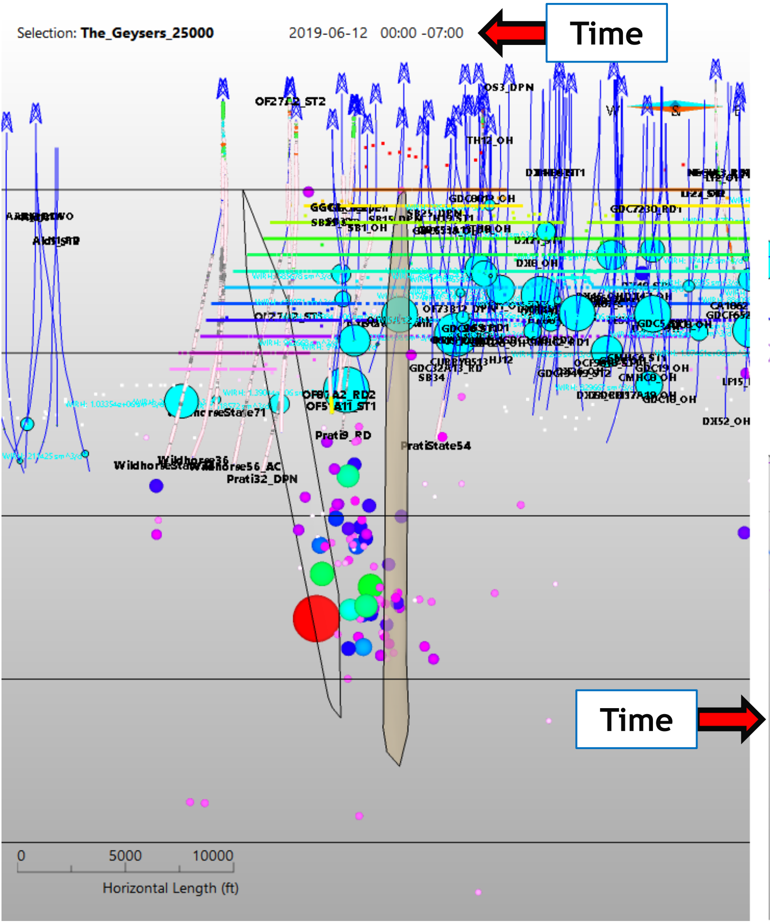
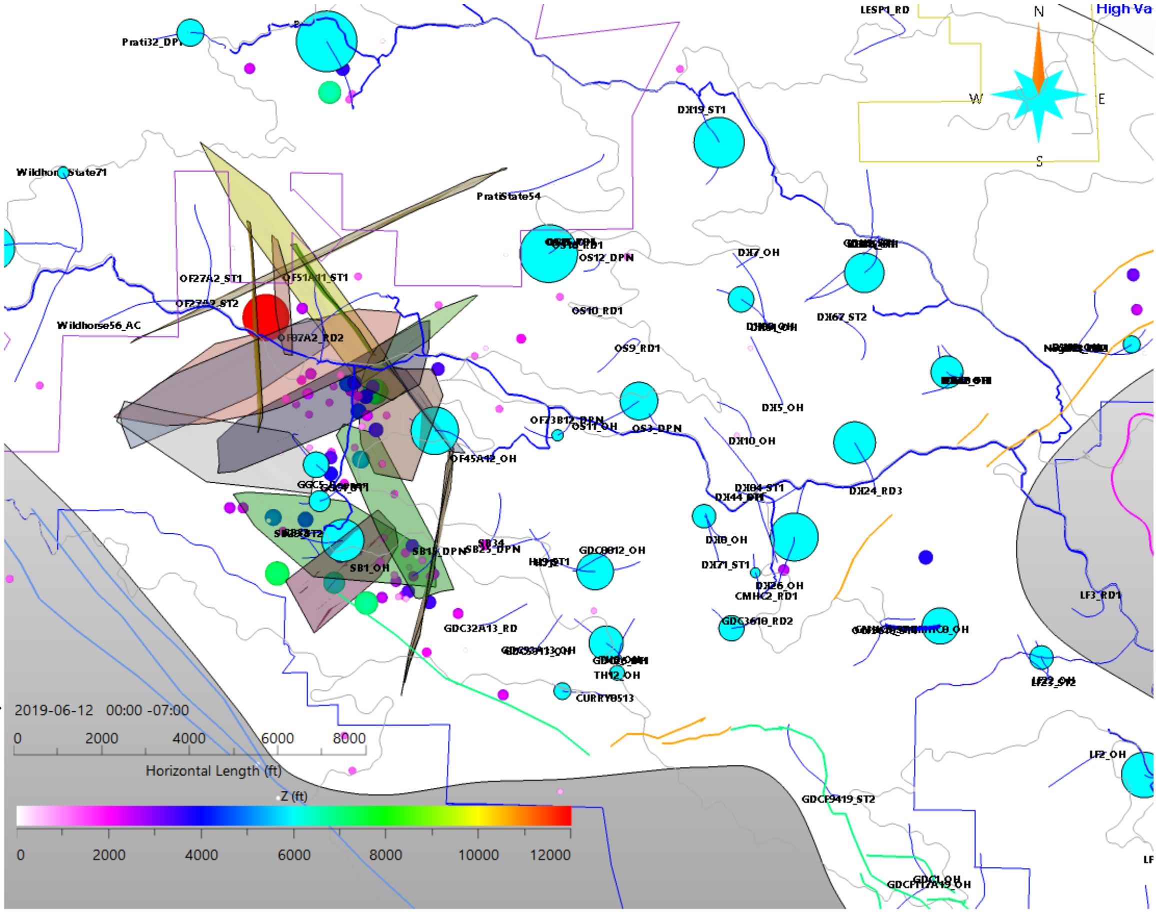
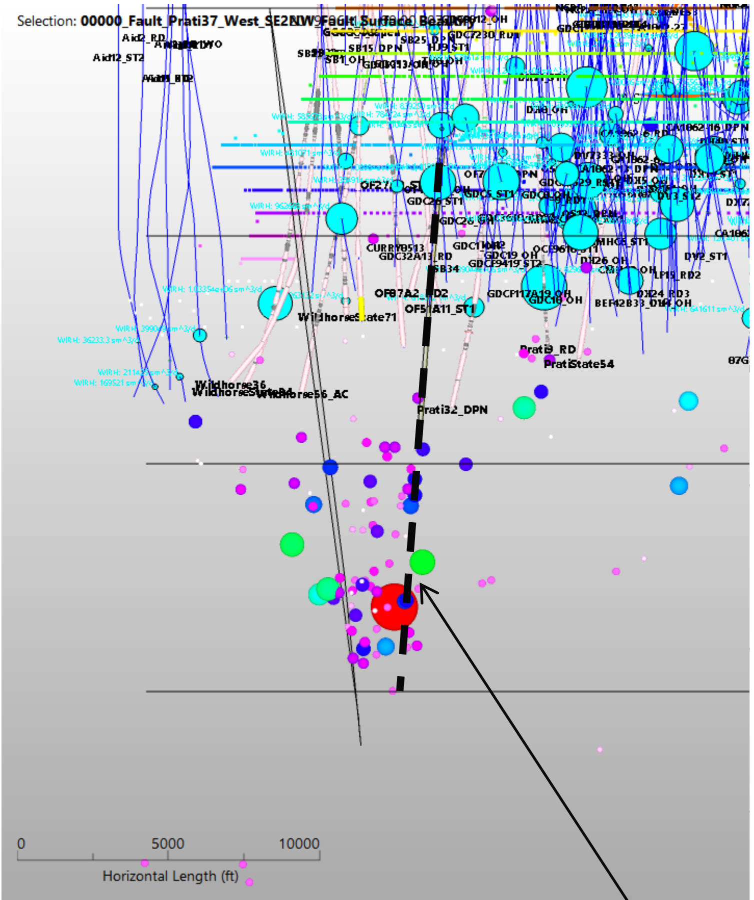
Detailed Analysis of 11 June 2019 Magnitude 4.07 Seismic Event

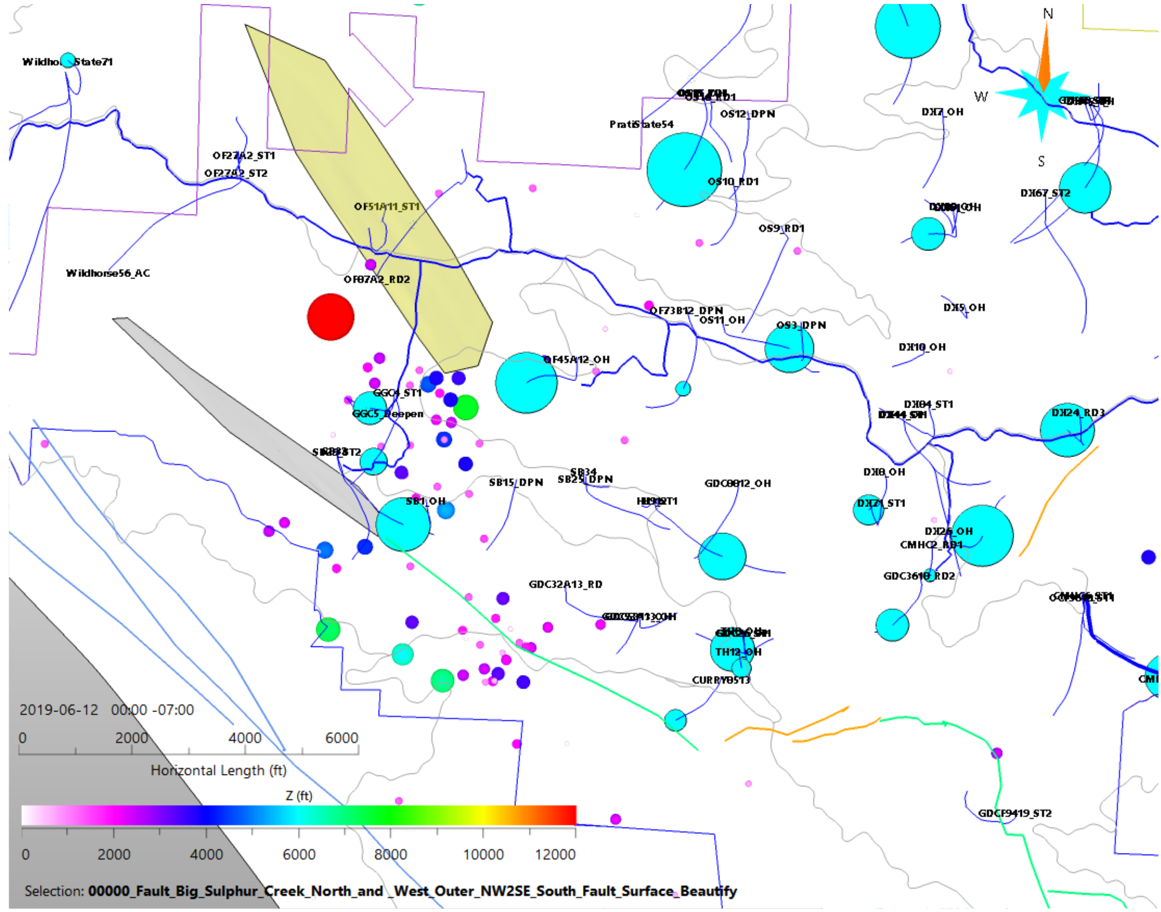
After 4.07 Seismic Event, Subsequent Seismicity Hypocenters Seem To Progress Within Fracture Zones And Structural Domains Previously Defined By Historical Seismicity Alignments





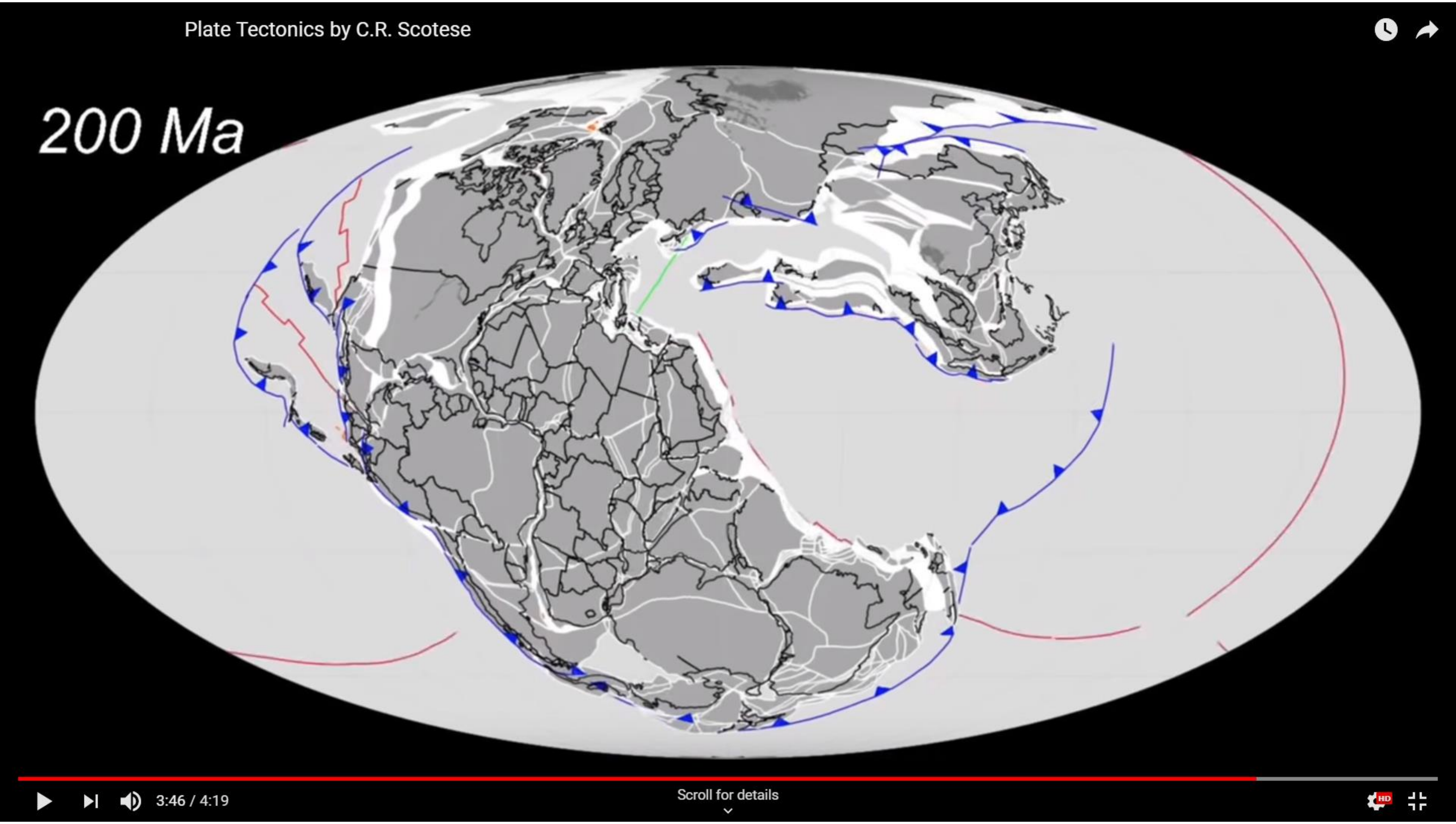
Detailed Analysis of 11 June 2019 Magnitude 4.07 Seismic Event





11 June 2019 Seismicity Hypocenters Seems To Define or "Illuminate" This Fracture Zone To A Greater Depth.

Plate Tectonic Evolution from Pangea to Modern Continental Configuration 200 Million Years Ago to Present (x 10)



From: Scotese, C.R., and Elling, R.P., 2017. Plate Tectonic Evolution during the last 1.5 Billion Years: The Movie. Plate Tectonics at 50, William Smith Meeting, October 3-5, 2017, The Geological Society, Burlington House, London, p. 16-17.

Plate Tectonic Evolution from Pangea to Modern Continental Configuration 200 Million Years Ago to Present (x 10)

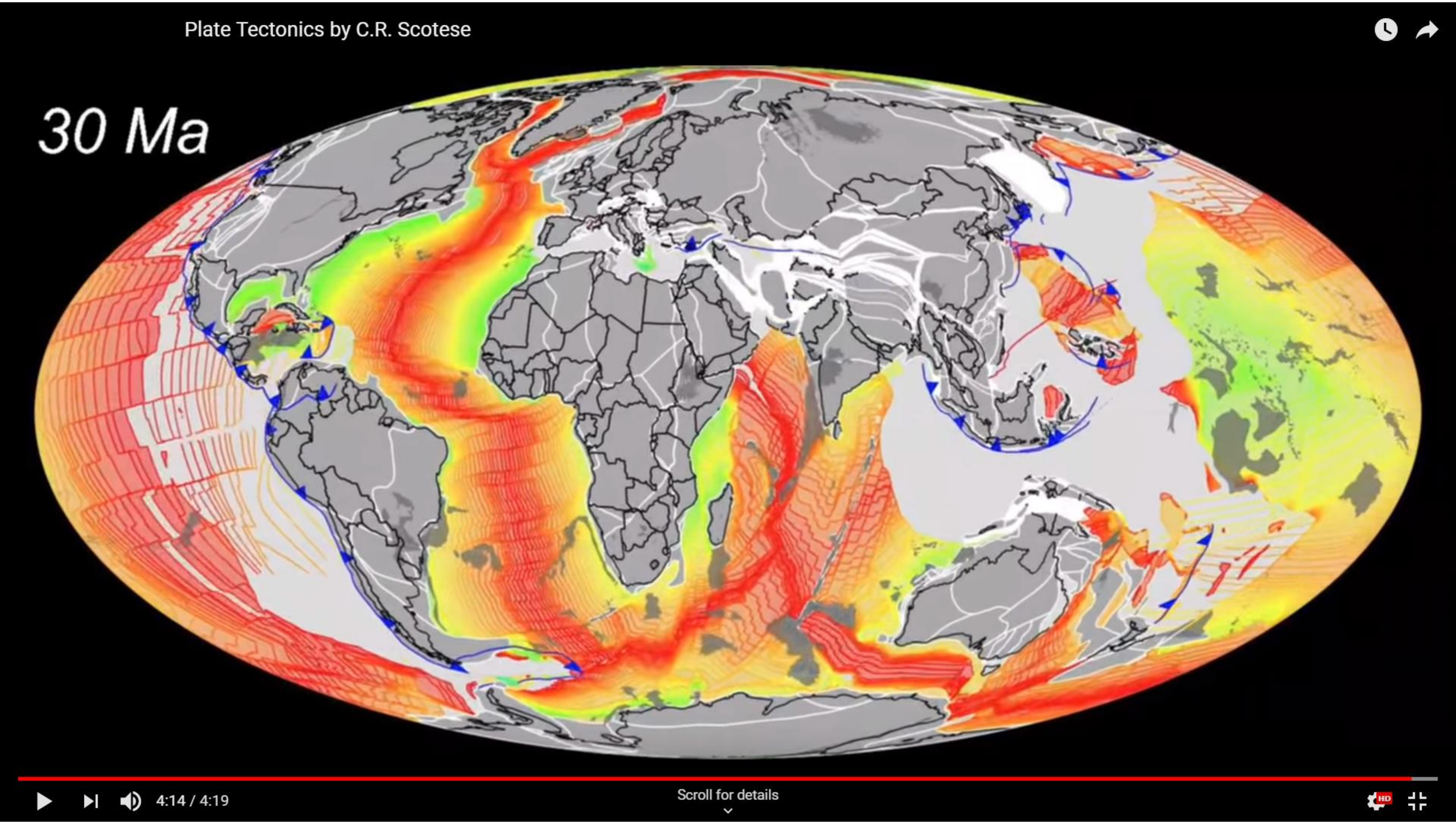


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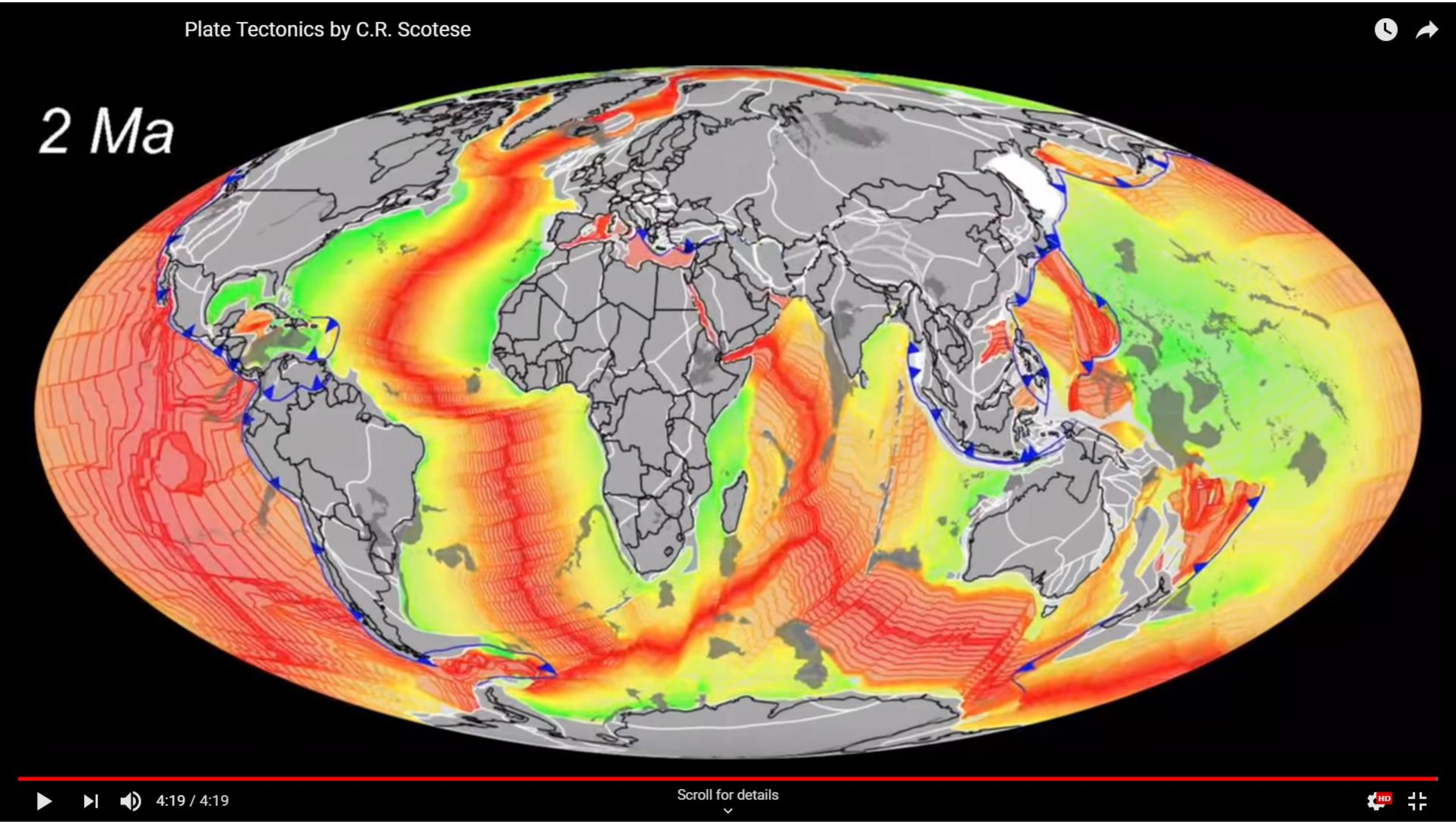
Plate Tectonic Evolution from Pangea to Modern Continental Configuration 200 Million Years Ago to Present (x 10)



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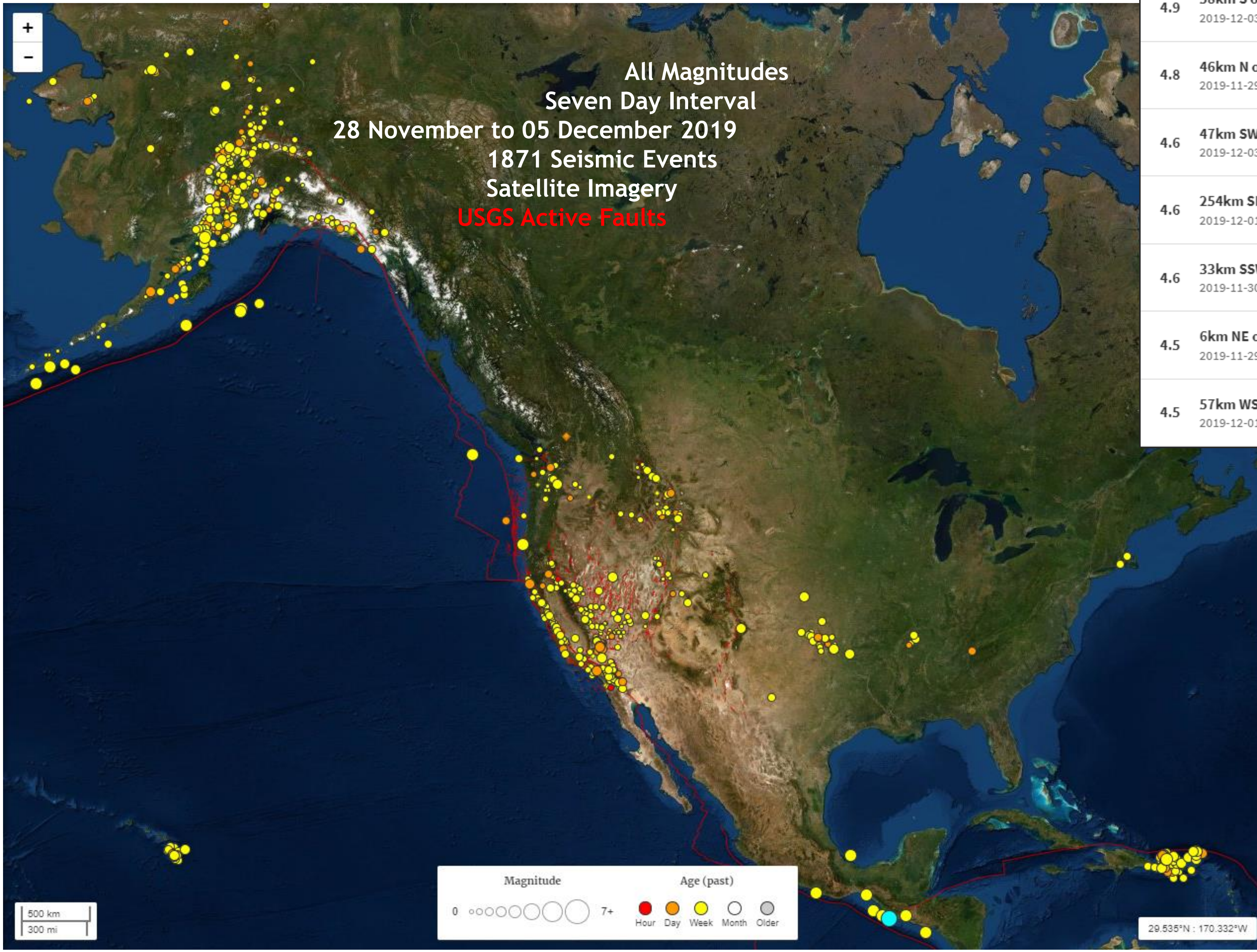
U.S. Geological Survey Latest Earthquakes

5.6	41km S of Champerico, Guatemala 2019-11-29 23:44:25 (UTC-08:00	47.6 km
4.9	58km S of Puerto El Triunfo, El S... 2019-12-03 05:37:58 (UTC-08:00	48.4 km
4.8	46km N of San Antonio, Puerto R... 2019-11-29 07:08:44 (UTC-08:00	37.0 km
4.6	47km SW of Ocos, Guatemala 2019-12-03 08:11:05 (UTC-08:00	10.0 km
4.6	254km SE of Kodiak, Alaska 2019-12-01 21:46:40 (UTC-08:00	10.0 km
4.6	33km SSW of Champerico, Guate... 2019-11-30 09:59:16 (UTC-08:00	41.4 km
4.5	6km NE of Port Orford, Oregon 2019-11-29 17:45:12 (UTC-08:00	16.6 km
4.5	57km WSW of Anchor Point, Alaska 2019-12-01 04:27:52 (UTC-08:00	89.2 km



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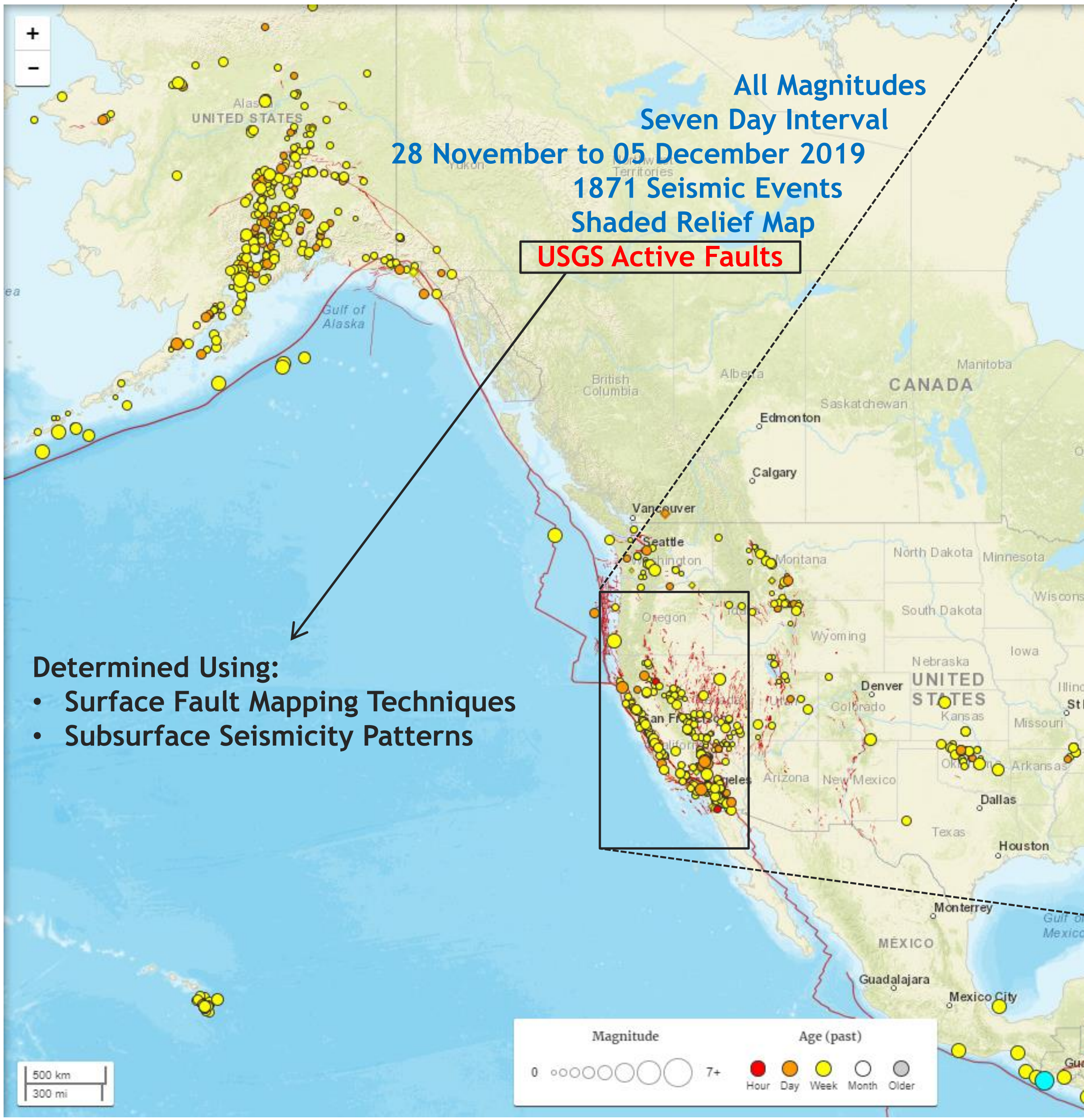
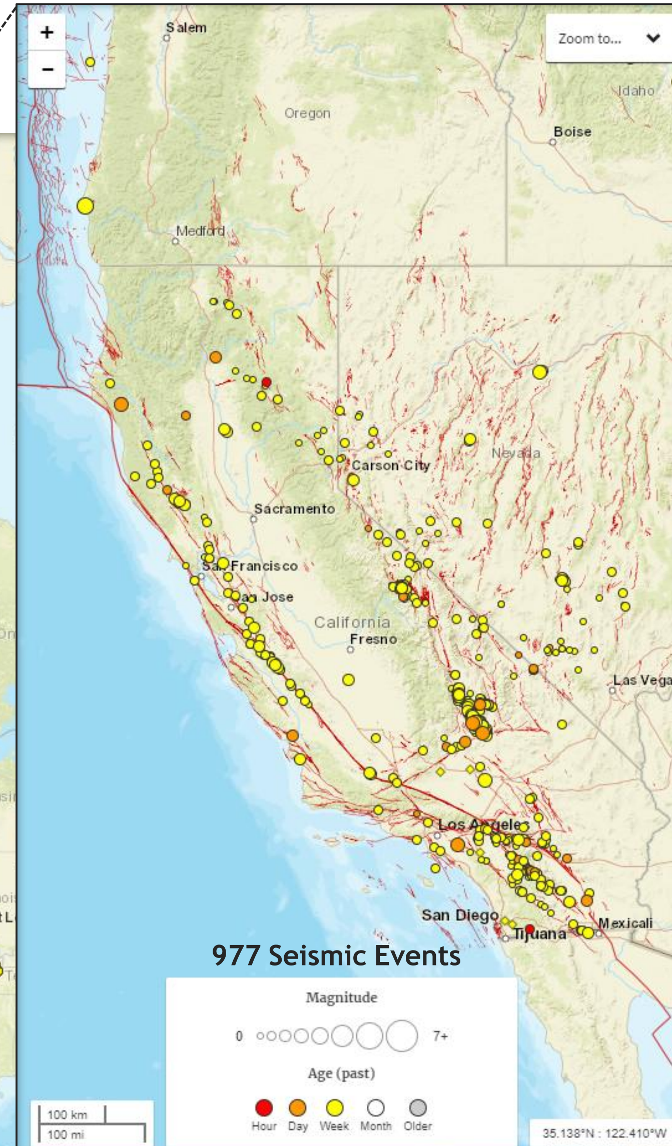
U.S. Geological Survey Latest Earthquakes

All Magnitudes
Seven Day Interval
28 November to 05 December 2019
1871 Seismic Events
Shaded Relief Map
USGS Active Faults



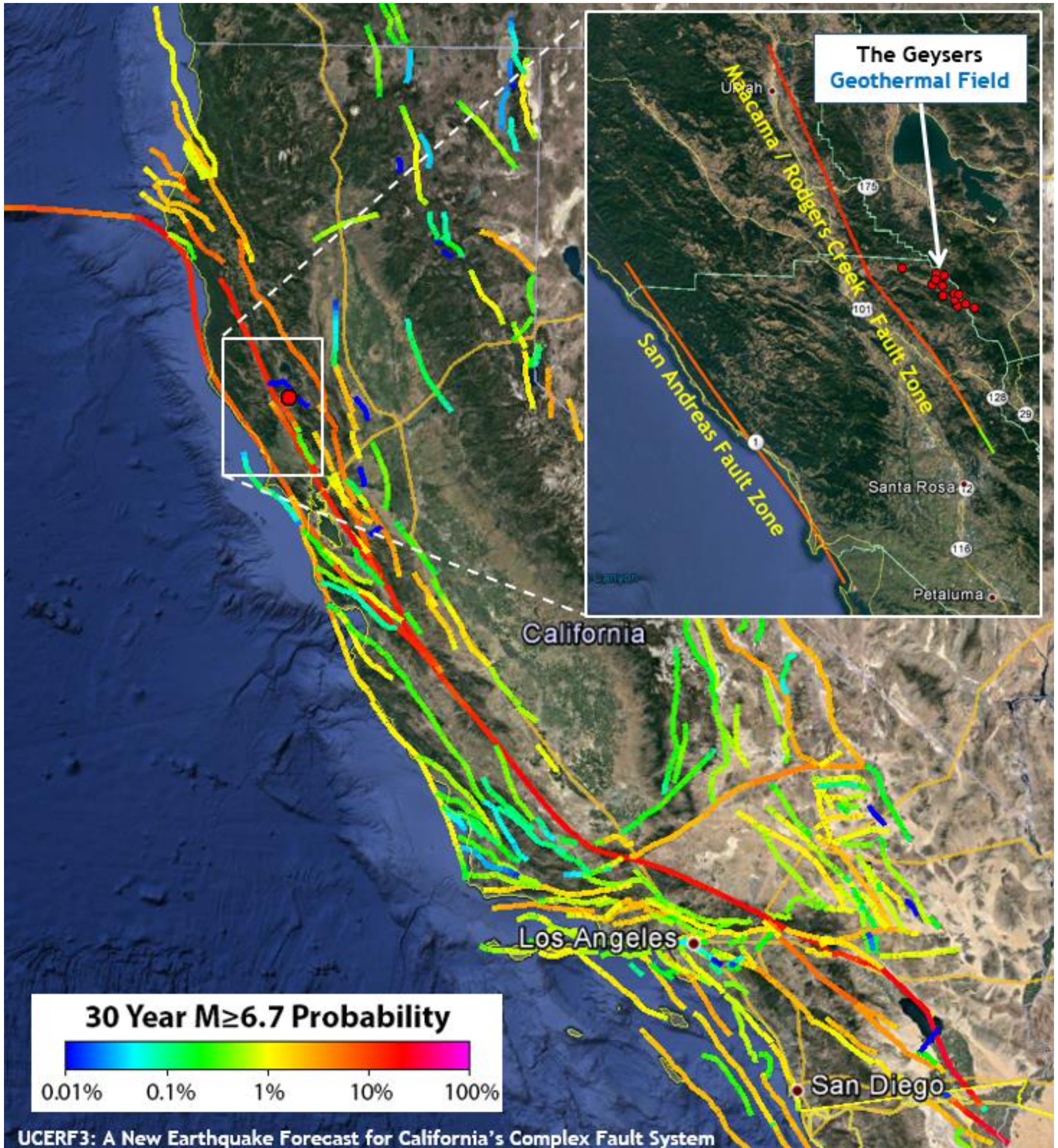
Determined Using:

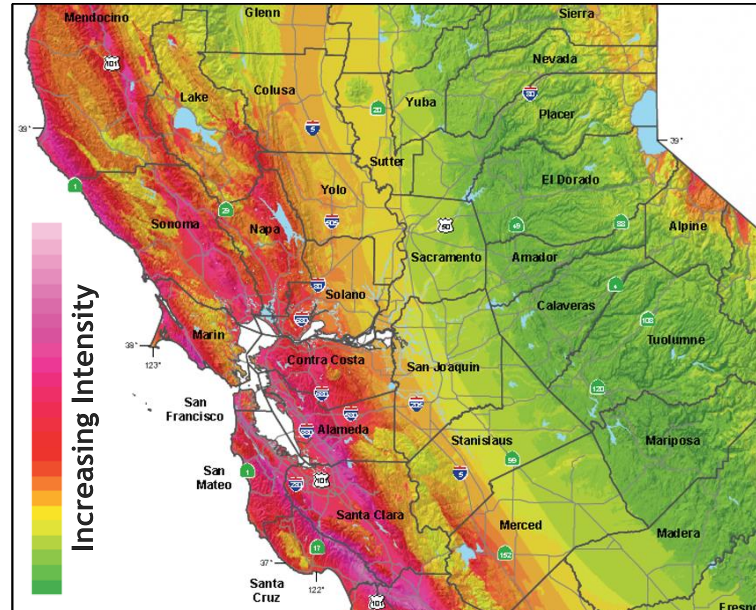
- Surface Fault Mapping Techniques
- Subsurface Seismicity Patterns



977 Seismic Events

U.S. Geological Survey Uniform California Earthquake Rupture Forecast 2016 Version 3 (UCERF3)





Portion of U.S. Geological Survey Digital Map "Earthquake Shaking Potential for California" (2016)

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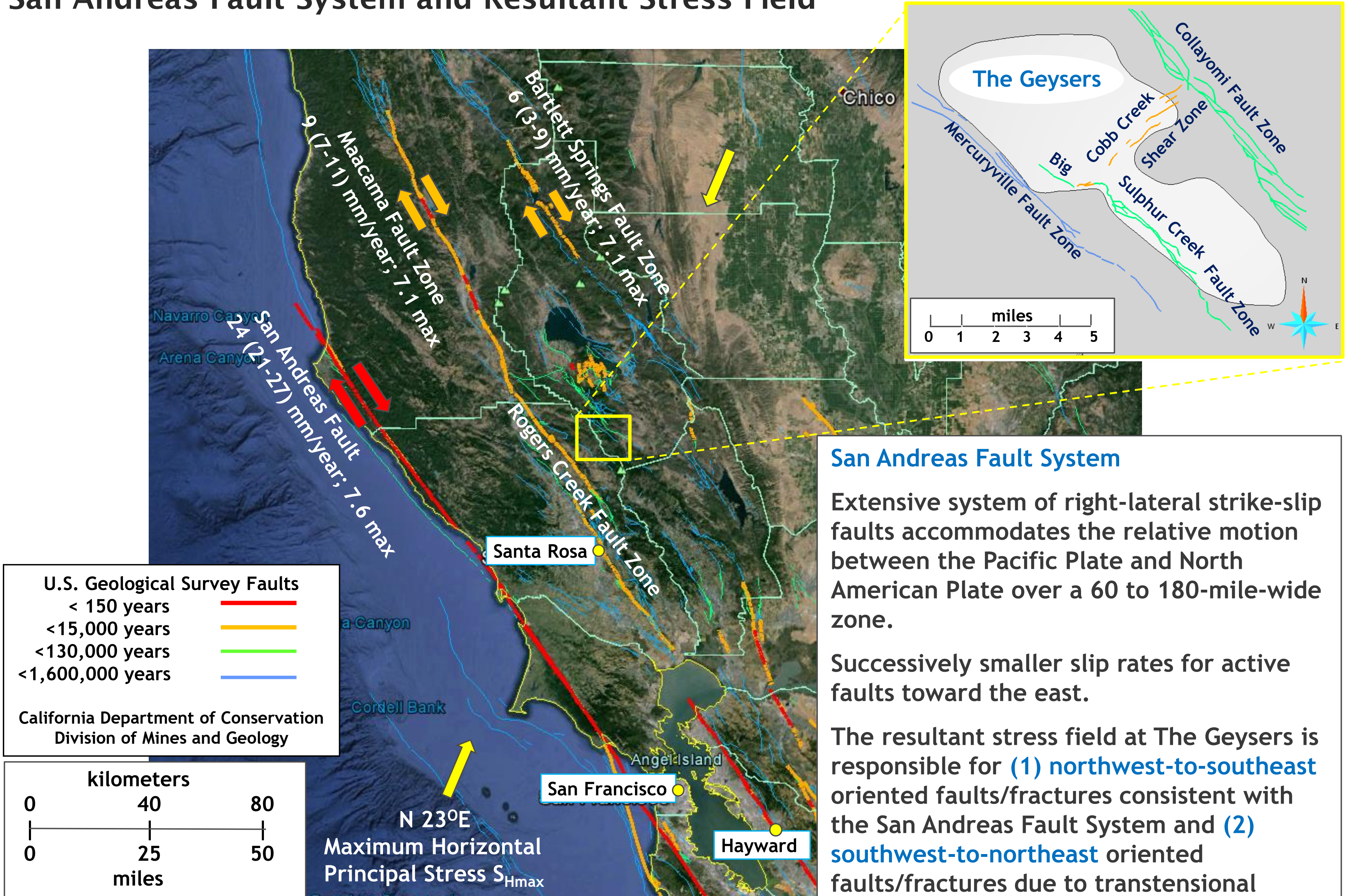
San Andreas Fault System and Resultant Stress Field



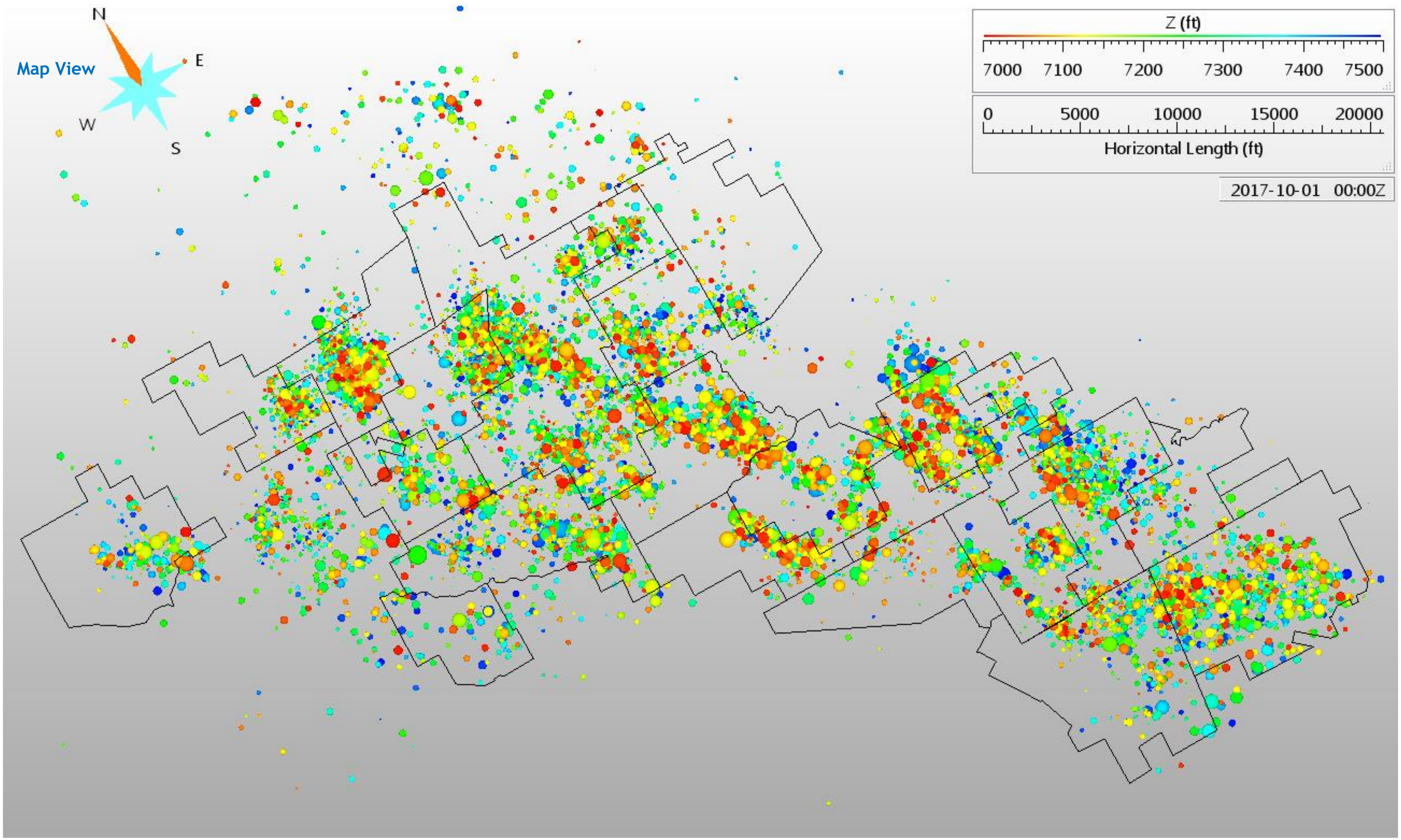
San Andreas Fault System

Extensive system of right-lateral strike-slip faults accommodates the relative motion between the Pacific Plate and North American Plate over a 60 to 180-mile-wide zone.

Successively smaller slip rates for active faults toward the east.

The resultant stress field at The Geysers is responsible for (1) northwest-to-southeast oriented faults/fractures consistent with the San Andreas Fault System and (2) southwest-to-northeast oriented faults/fractures due to transtensional forces.

Seismic Monitoring Advisory Committee Meeting
Fault/Fracture Analysis and Interpretation
Depth Slice 7000 to 7500 Feet Subsea



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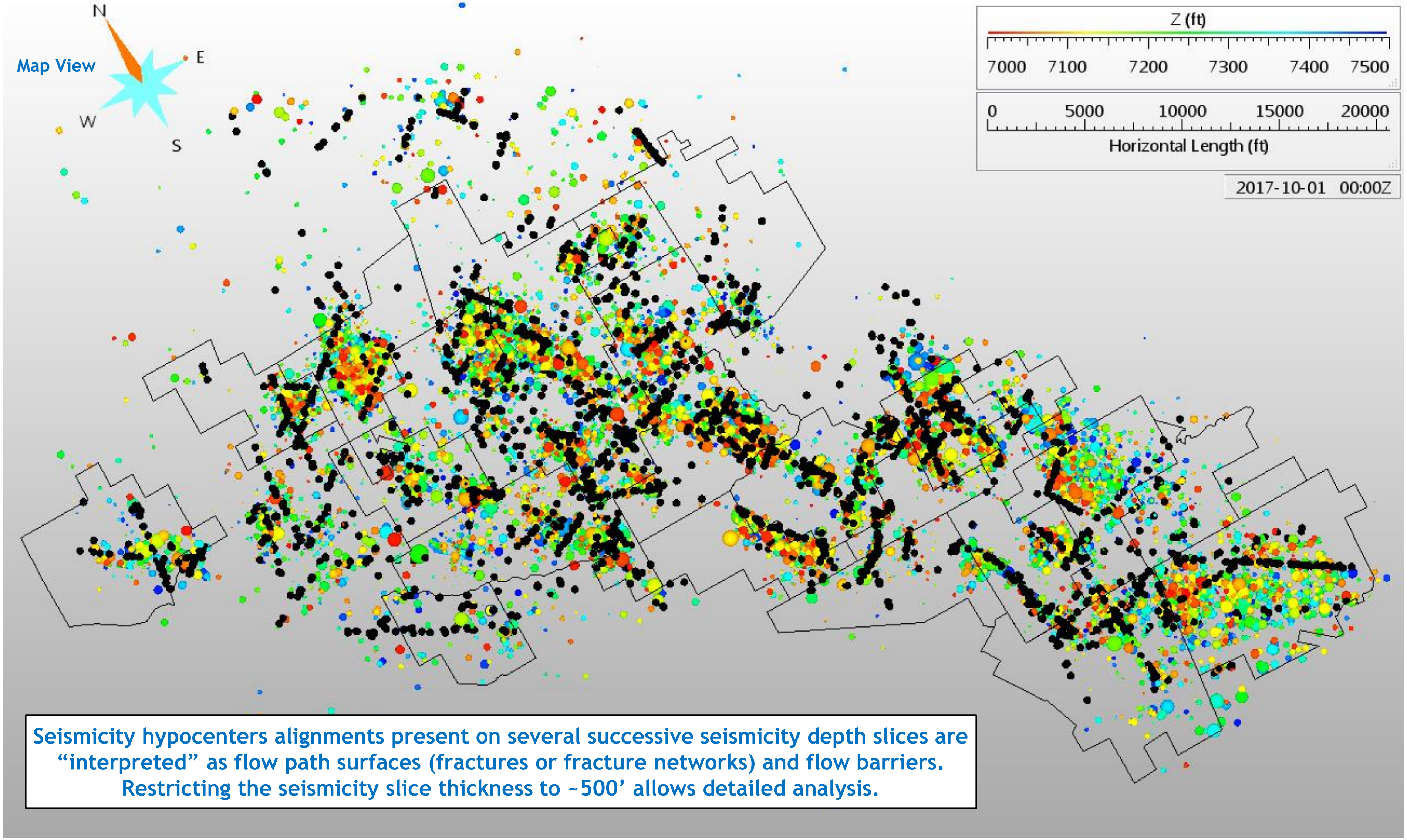
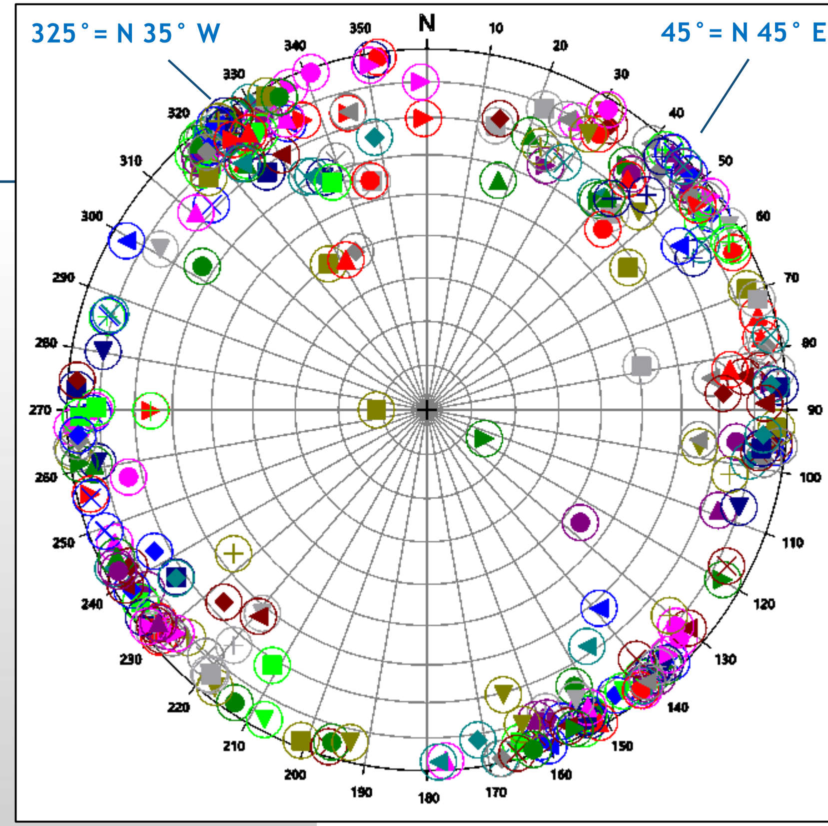
Fault/Fracture Analysis and Interpretation
Depth Slice 7000 to 7500 Feet Subsea



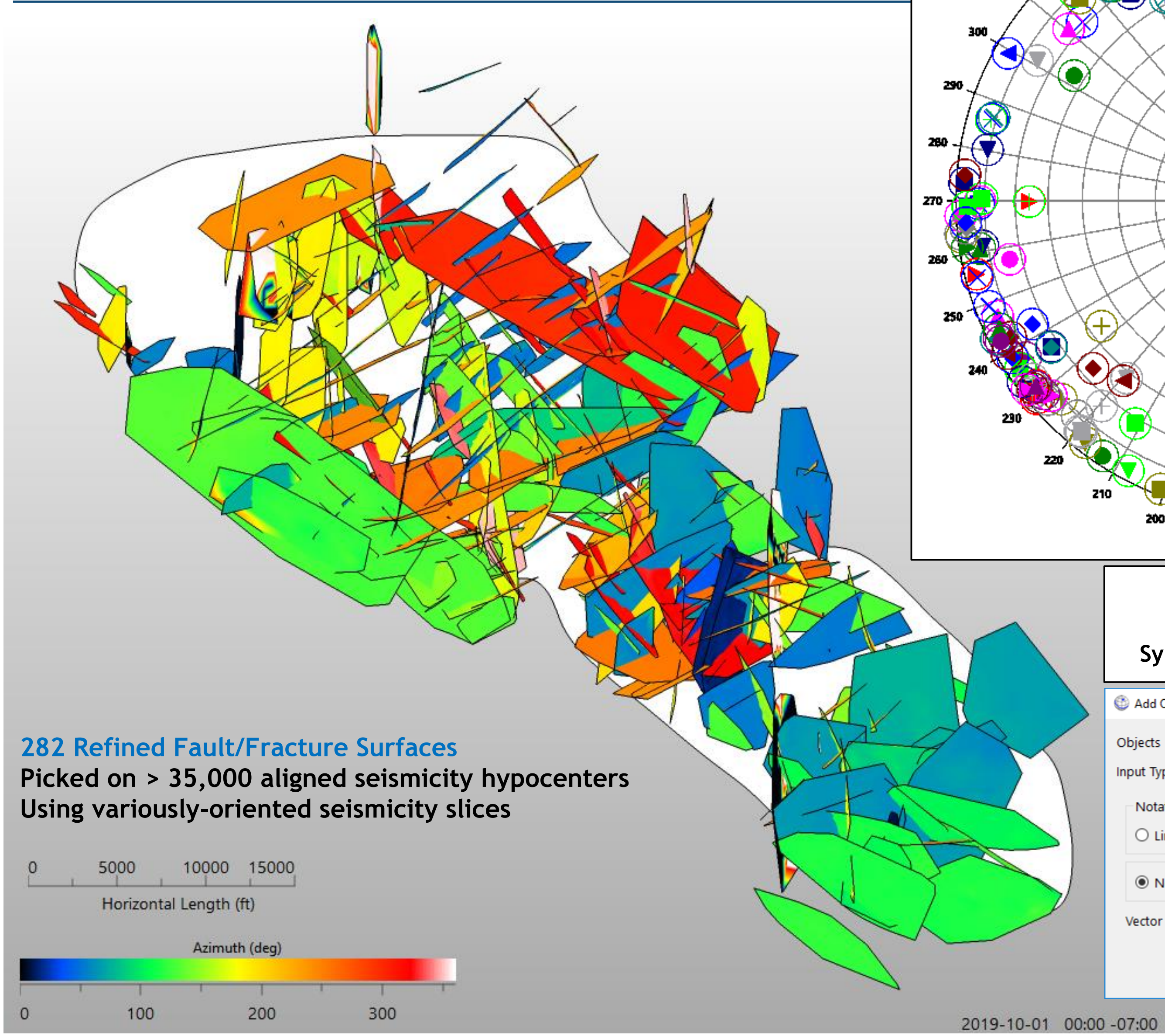
Seismicity hypocenters alignments present on several successive seismicity depth slices are "interpreted" as flow path surfaces (fractures or fracture networks) and flow barriers. Restricting the seismicity slice thickness to ~500' allows detailed analysis.

Seismic Monitoring Advisory Committee

282 Surfaces – Stereonet - Schmidt Diagram



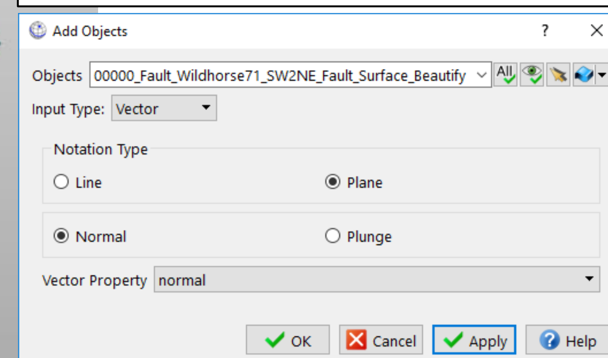
Interpreted Fault/Fracture Surfaces
Azimuth and Dip
Symbols Near Perimeter Are Near Vertical



282 Refined Fault/Fracture Surfaces

Picked on > 35,000 aligned seismicity hypocenters

Using variously-oriented seismicity slices



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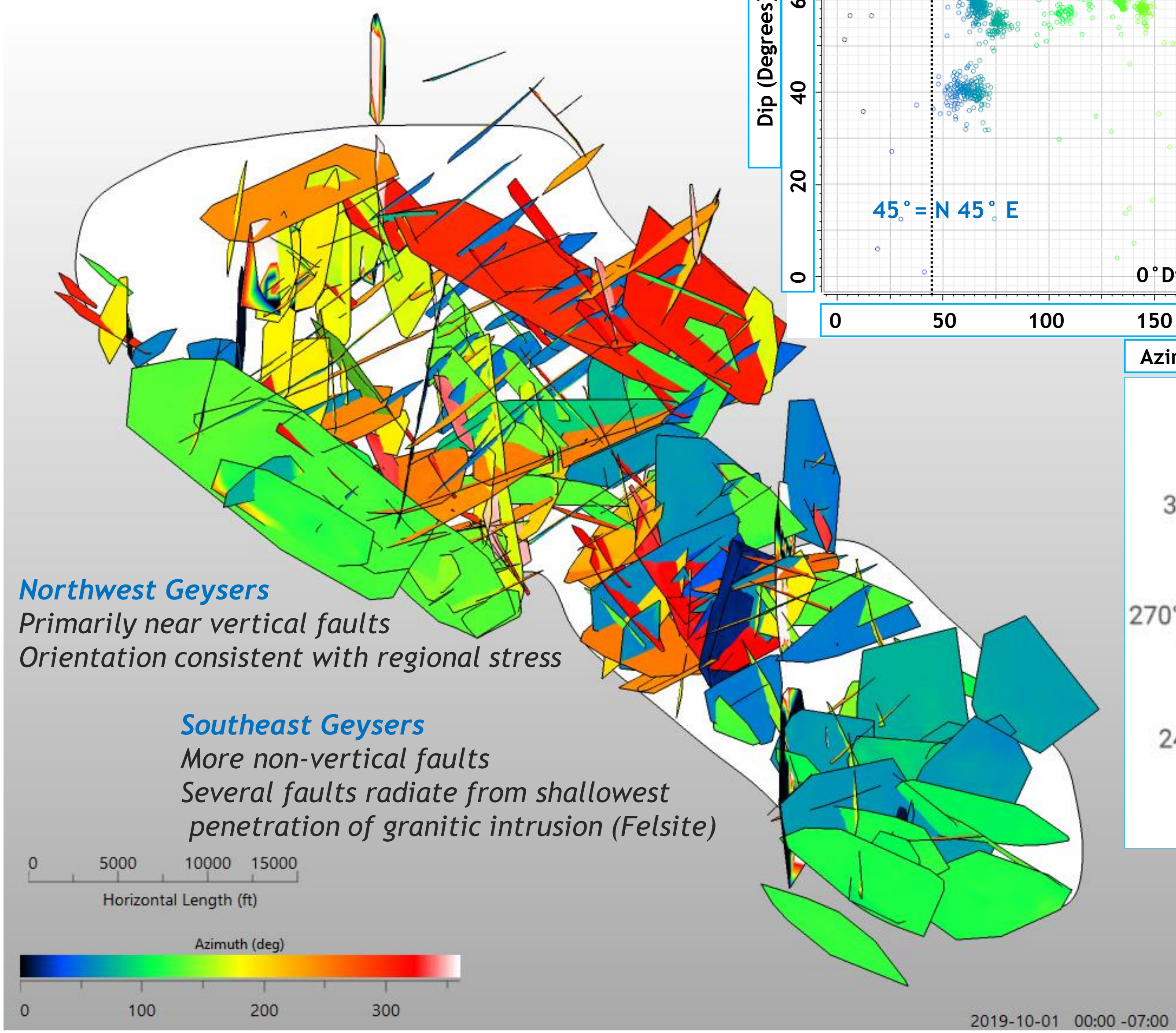
282 Surfaces – Azimuth and Dip



Northwest Geysers

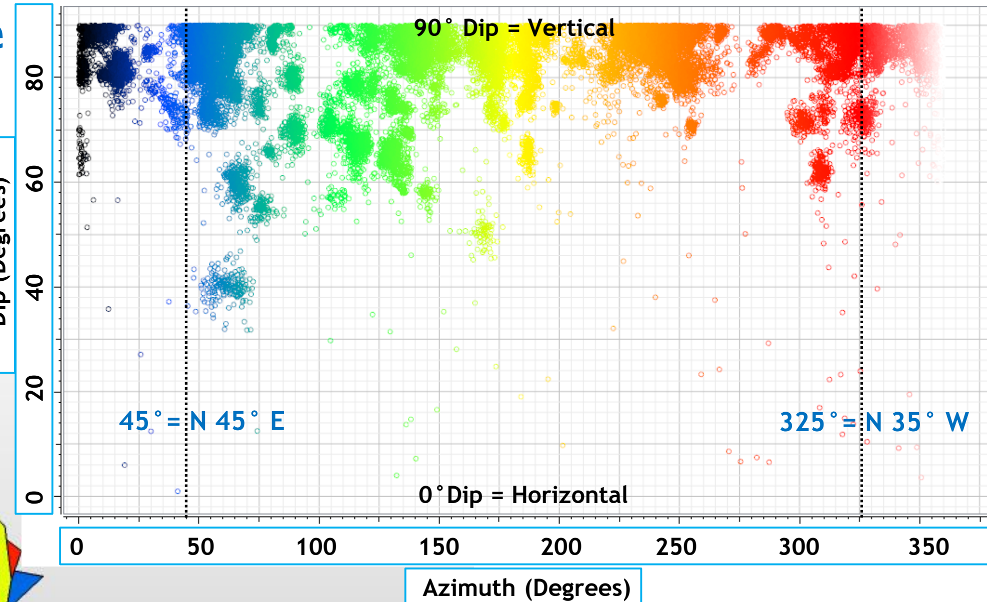
Primarily near vertical faults

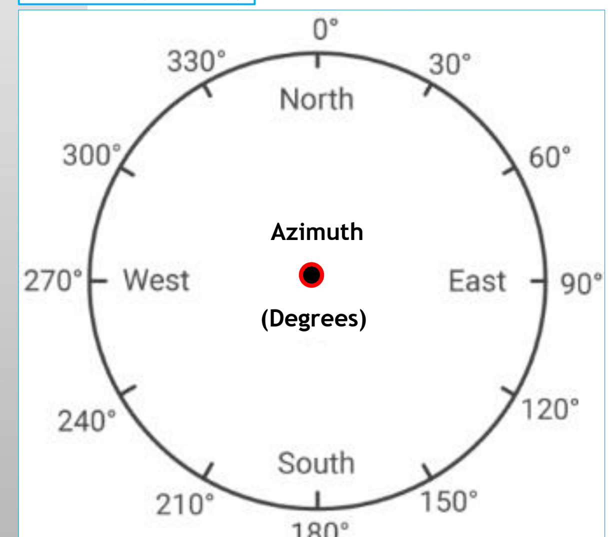
Orientation consistent with regional stress

Southeast Geysers

More non-vertical faults

Several faults radiate from shallowest penetration of granitic intrusion (Felsite)





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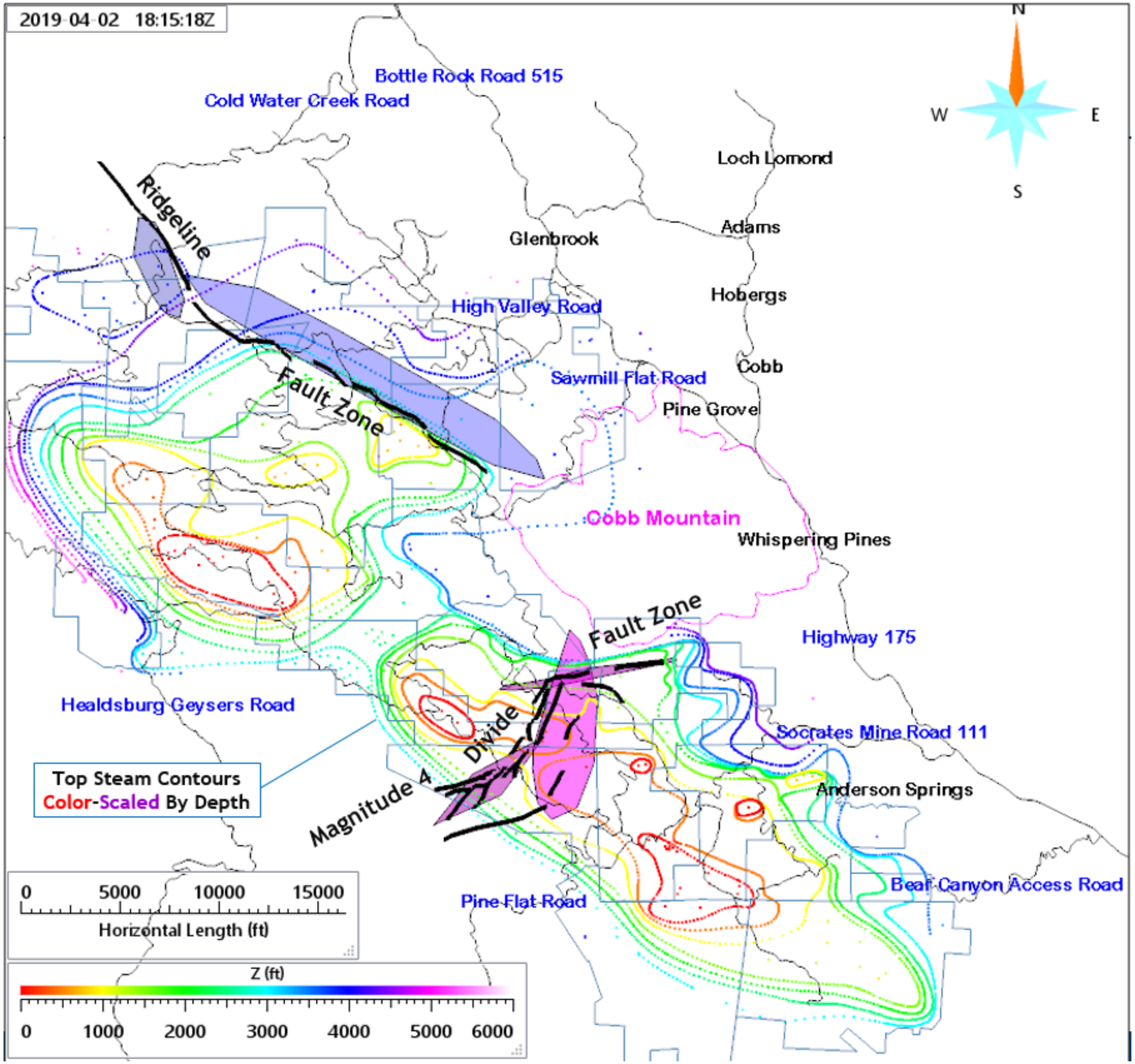
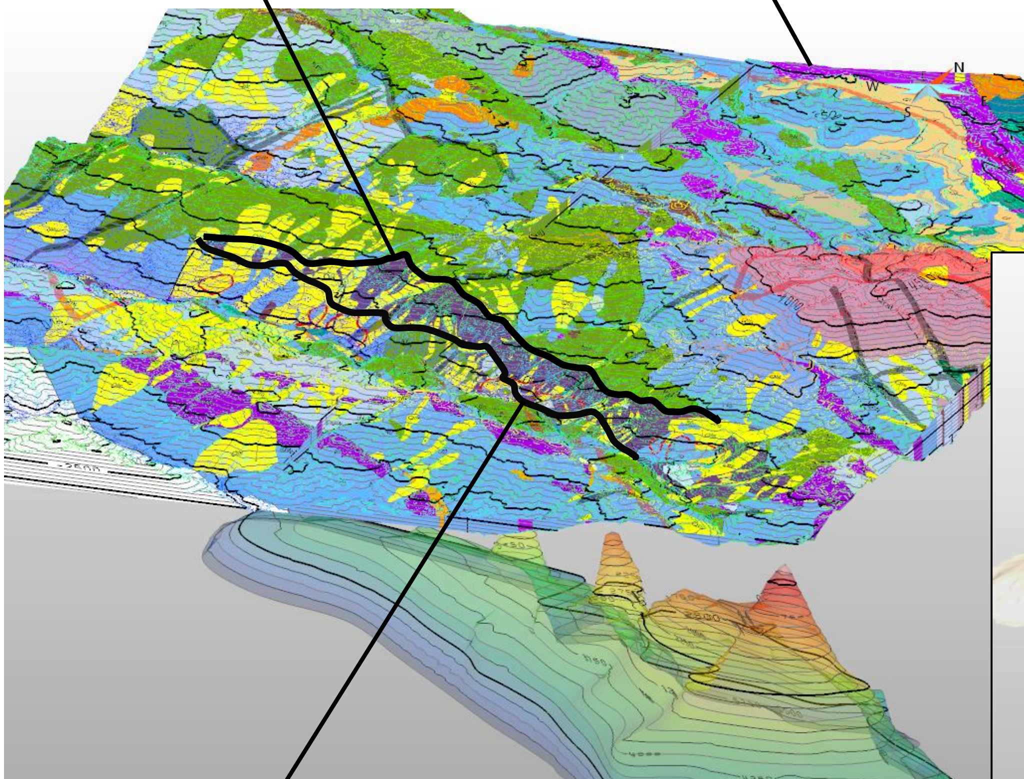
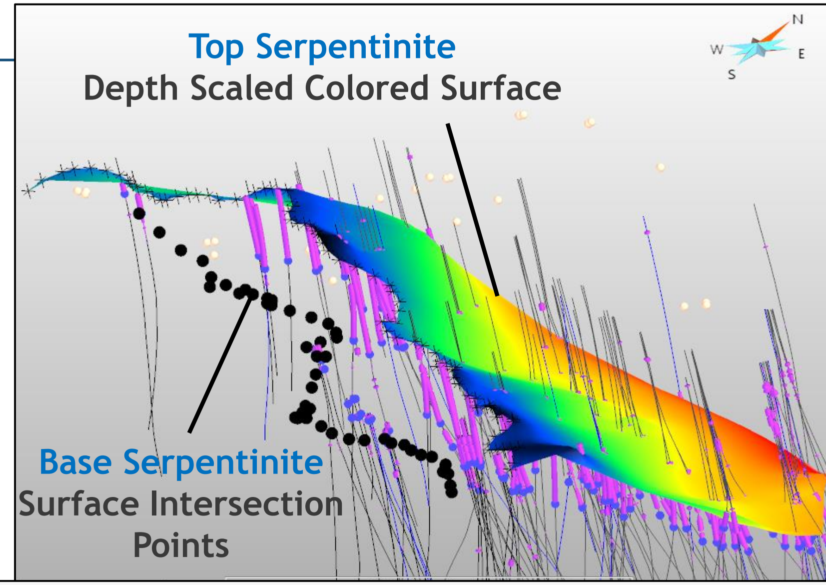
Mapped Surface Fault Zones Merged With Seismicity Slice Fracture Interpretation

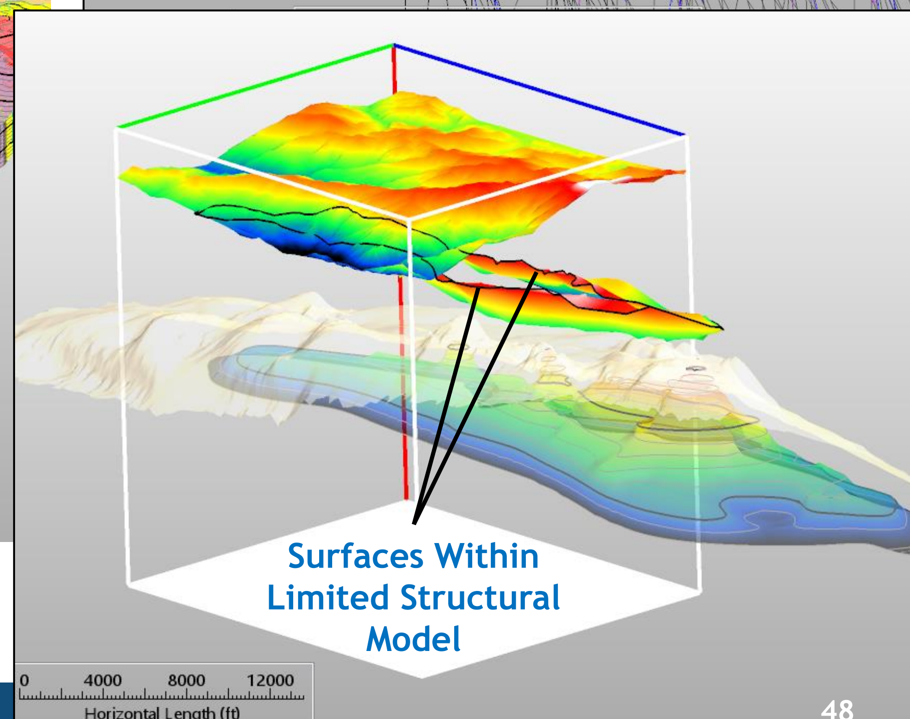
Magnitude 4 Divide Fault Zone and Ridgeline Fault Zone



Structural Model Building Constrained By Lithology Logs and ArcGIS Surface Geologic Map







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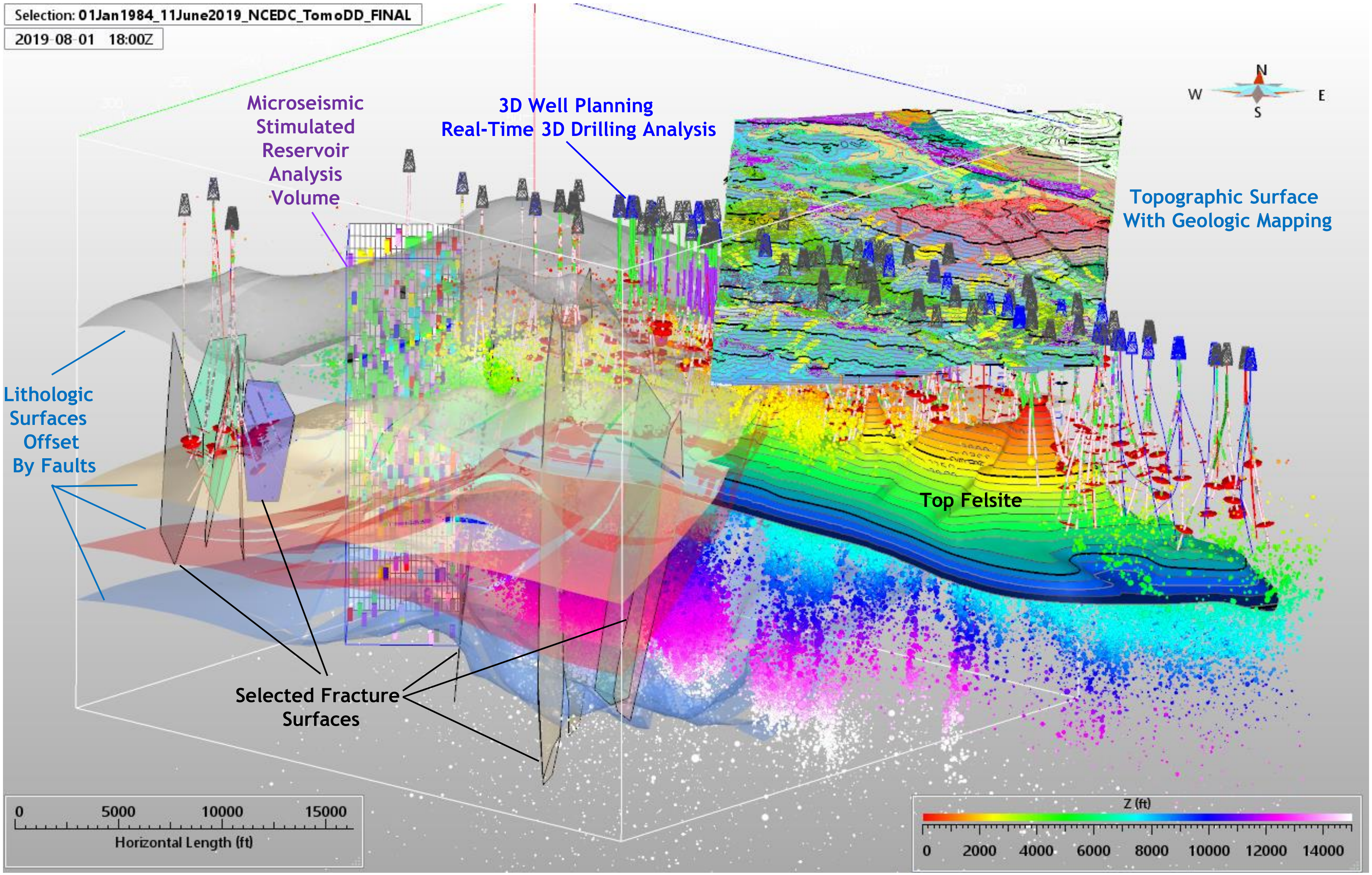
Current Status Of 3D Structural Model Development



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Voxet View from South
North Geysers 3D Structural Model

Topographic Surface

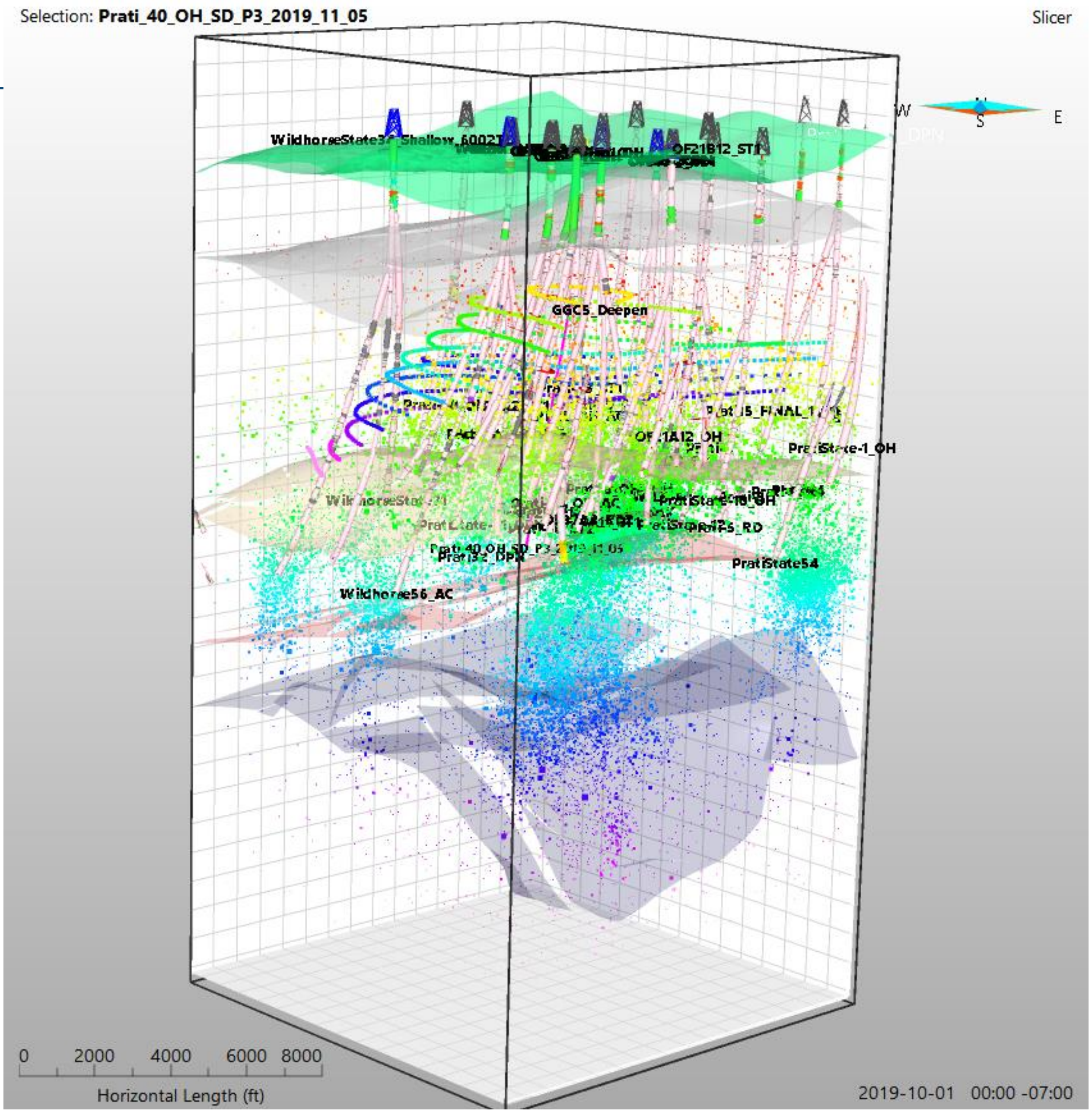
Top Main Graywacke

Top Steam Reservoir

Top Hornfelsic Graywacke

Top Granitic Intrusion (Felsite)

Base Steam Reservoir



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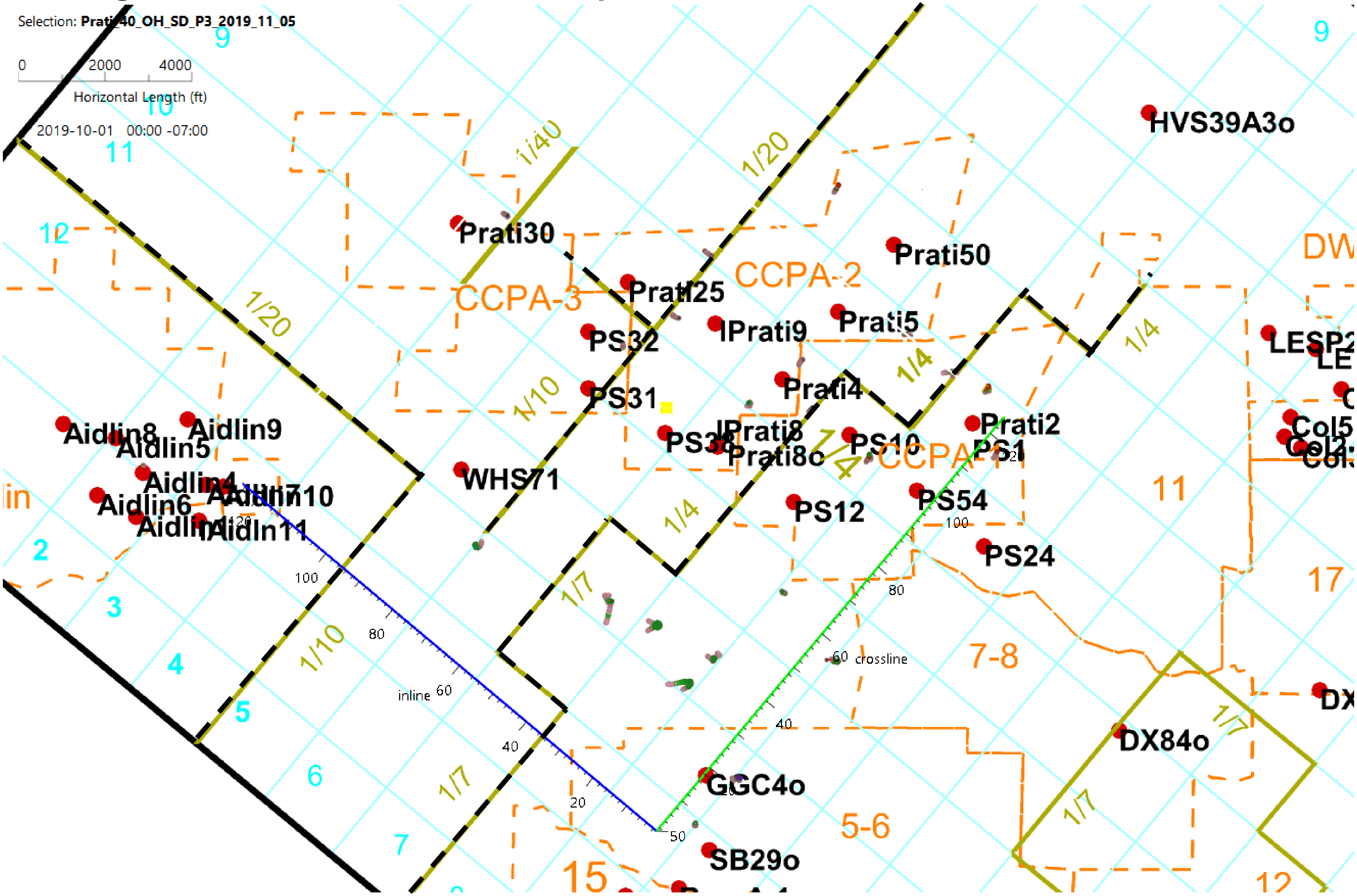
Relating Reservoir Flow Boundaries To Interpreted Fracture/Fault Zones



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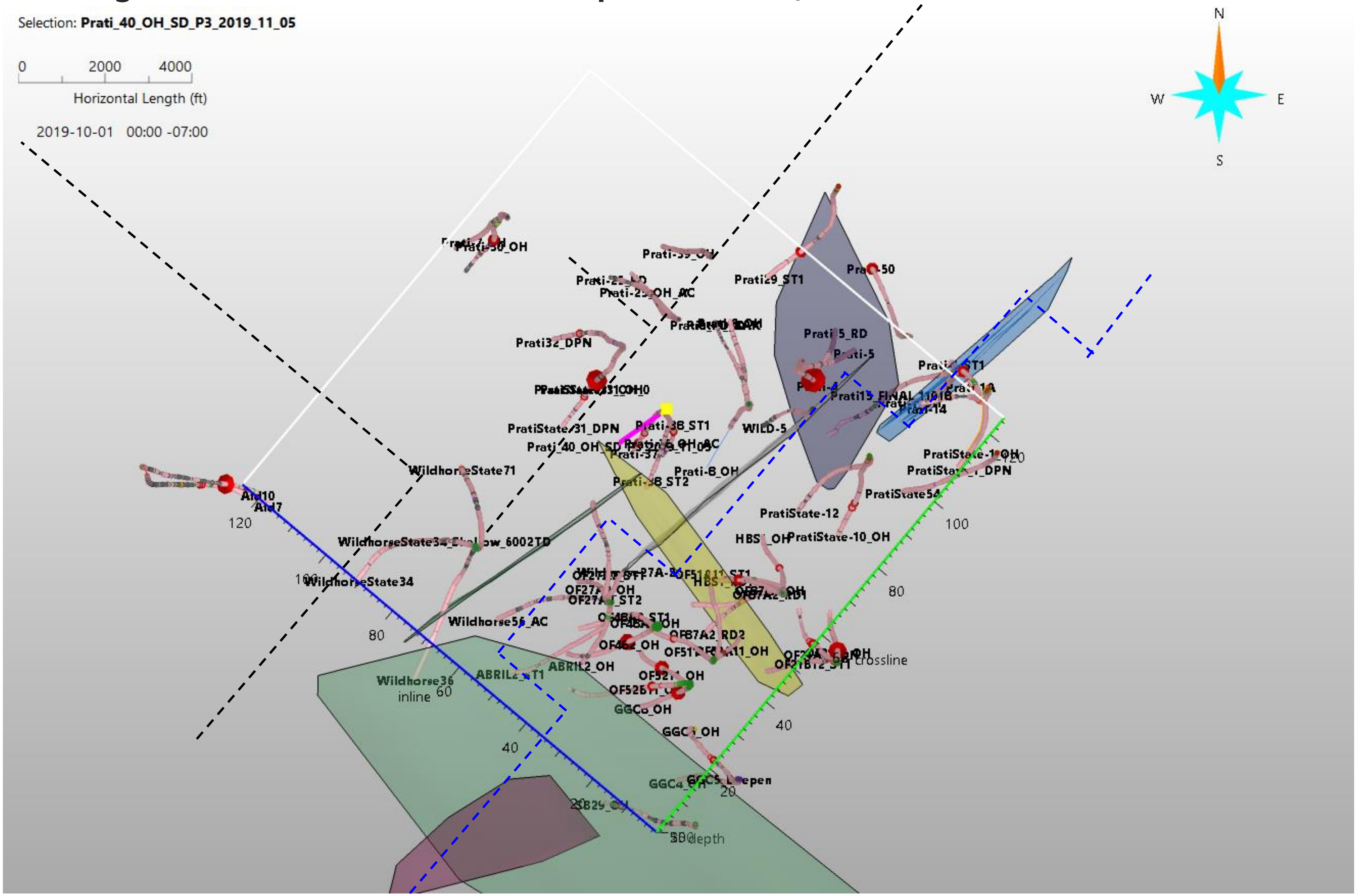
Relating Reservoir Flow Boundaries To Interpreted Fracture/Fault Zones



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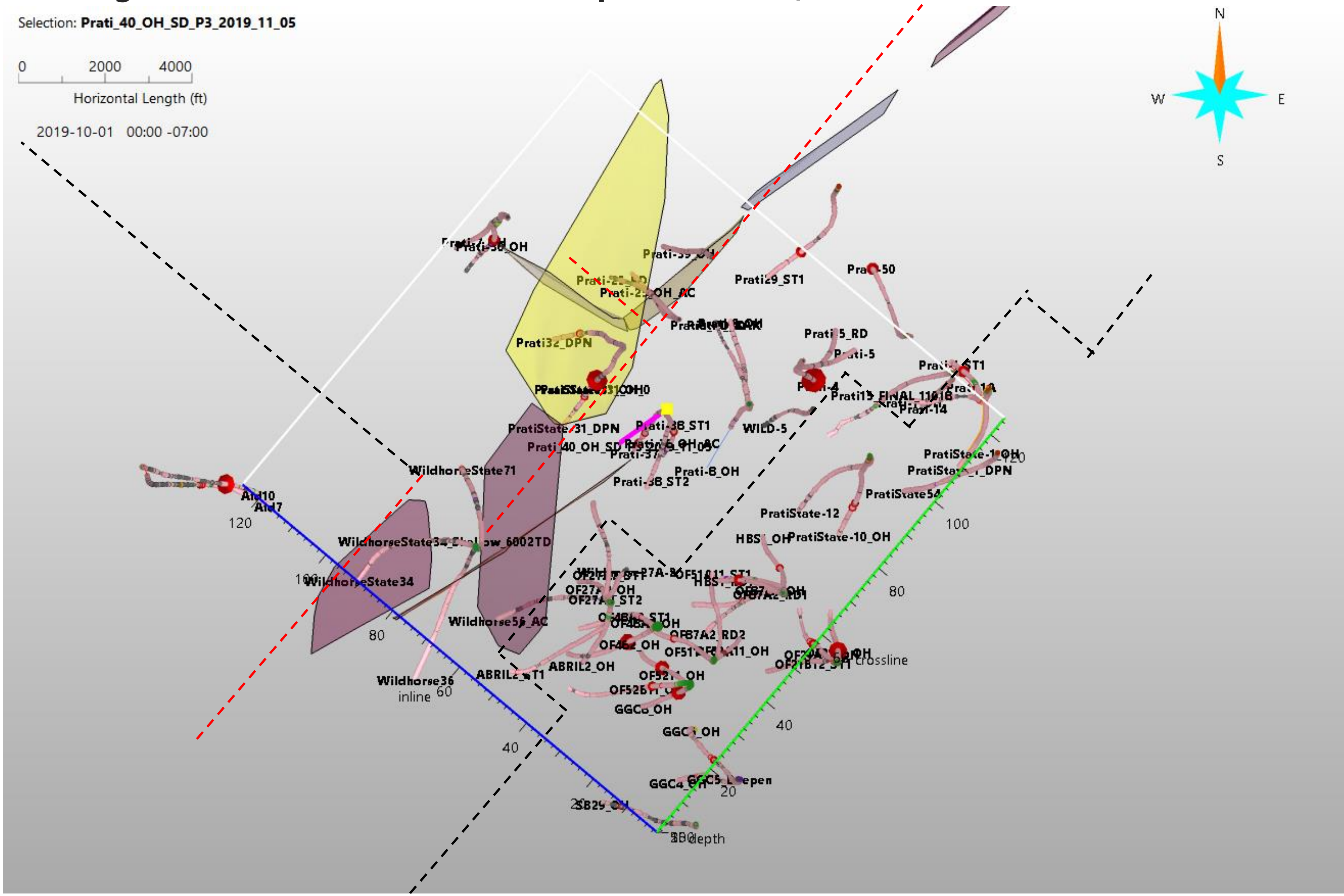
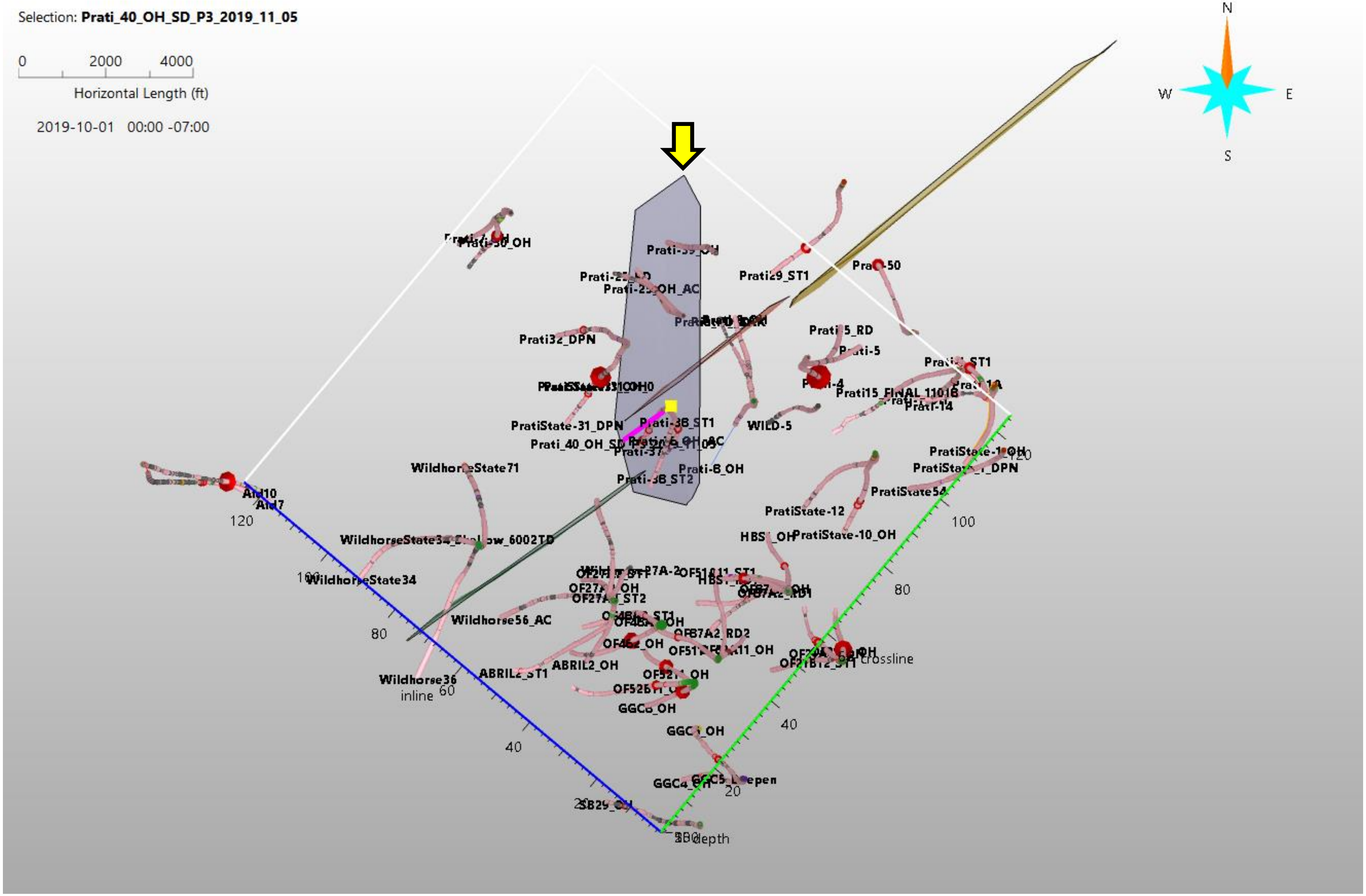
Relating Reservoir Flow Boundaries To Interpreted Fracture/Fault Zones



Seismic Monitoring Advisory Committee Meeting

Interpreted Fracture/Fault Zones Assessment



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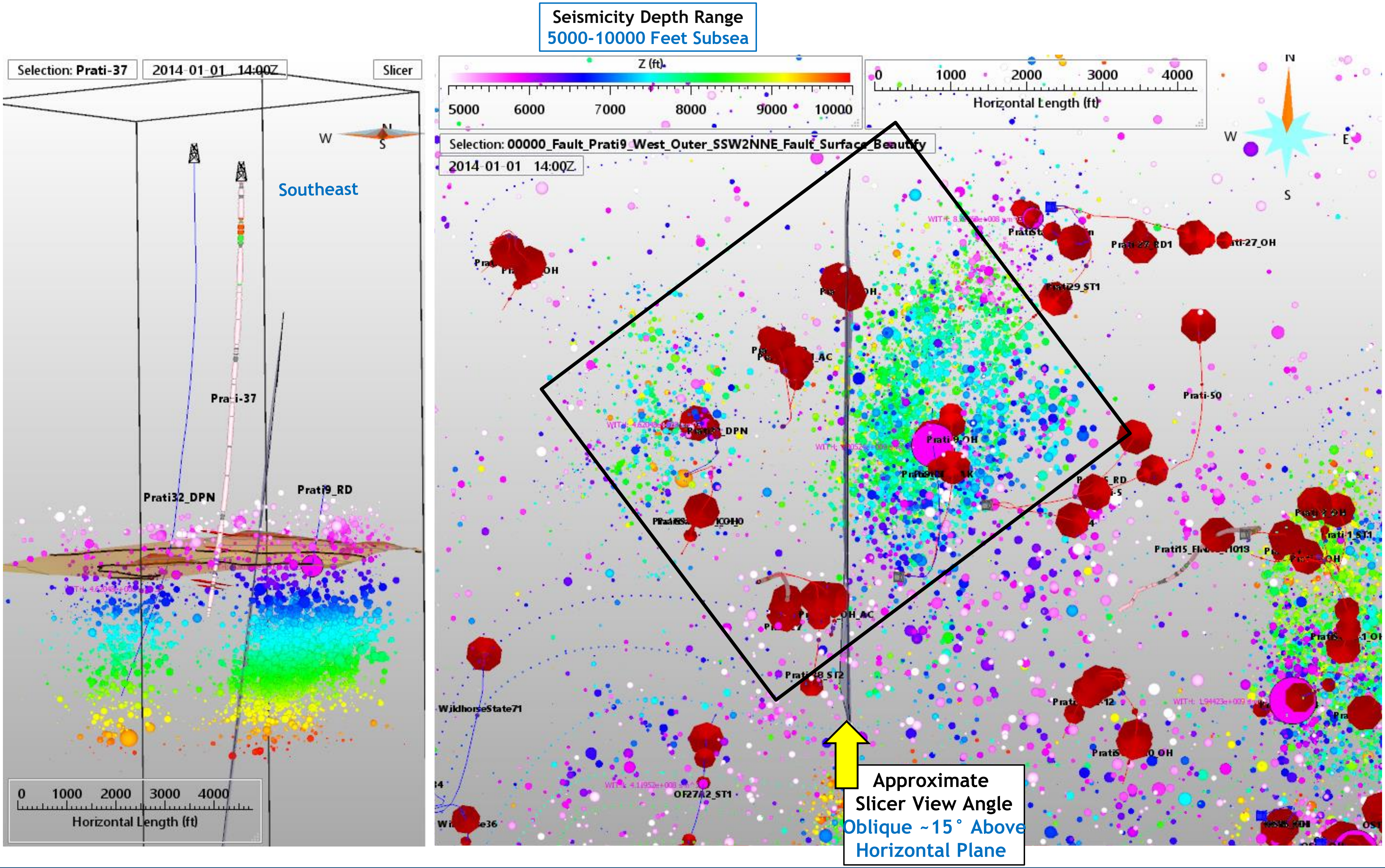
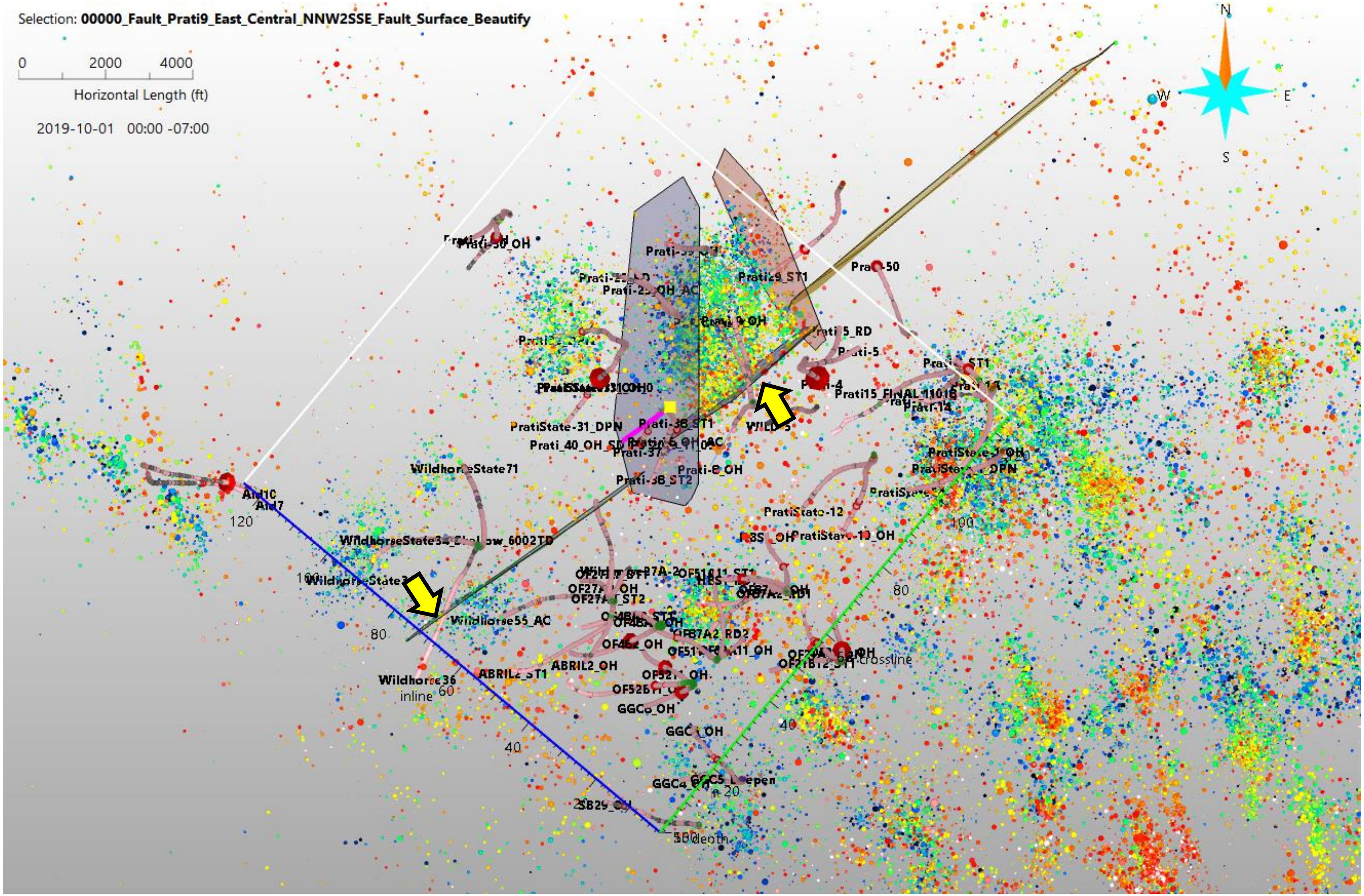
Interpreted Fracture/Fault Zones Assessment



Interpreted Fracture/Fault Zones Assessment



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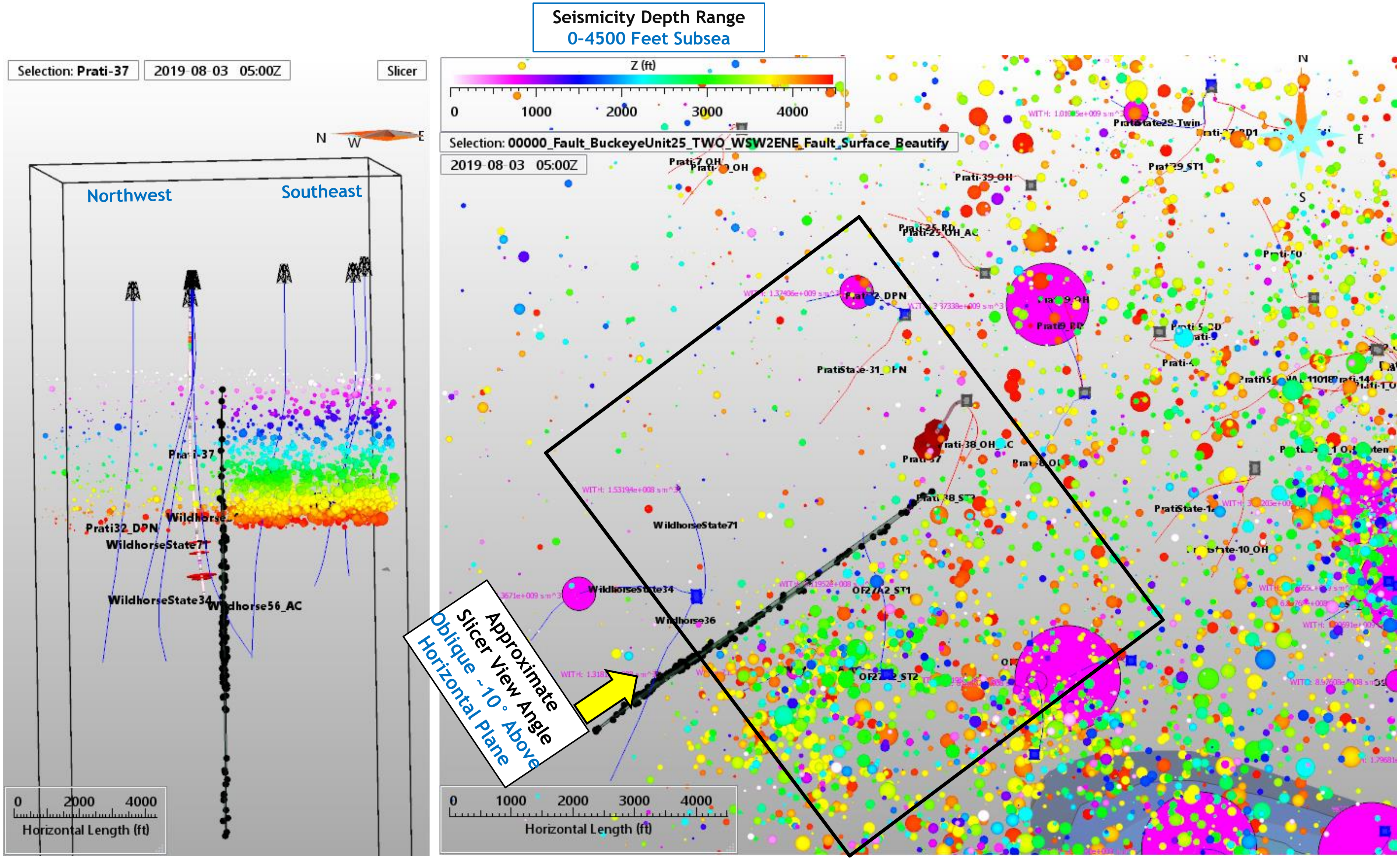
Interpreted Fracture/Fault Zones Assessment



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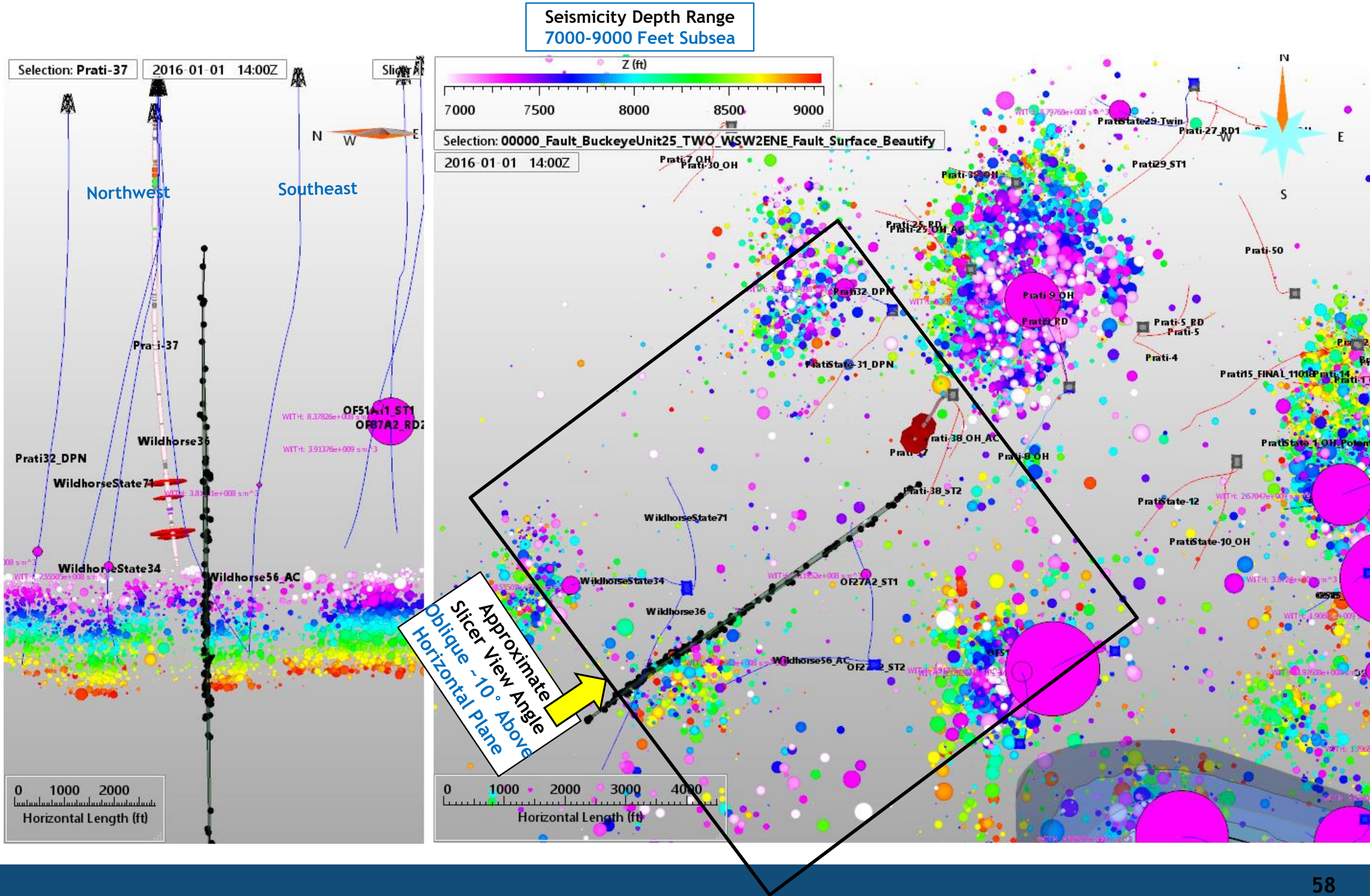
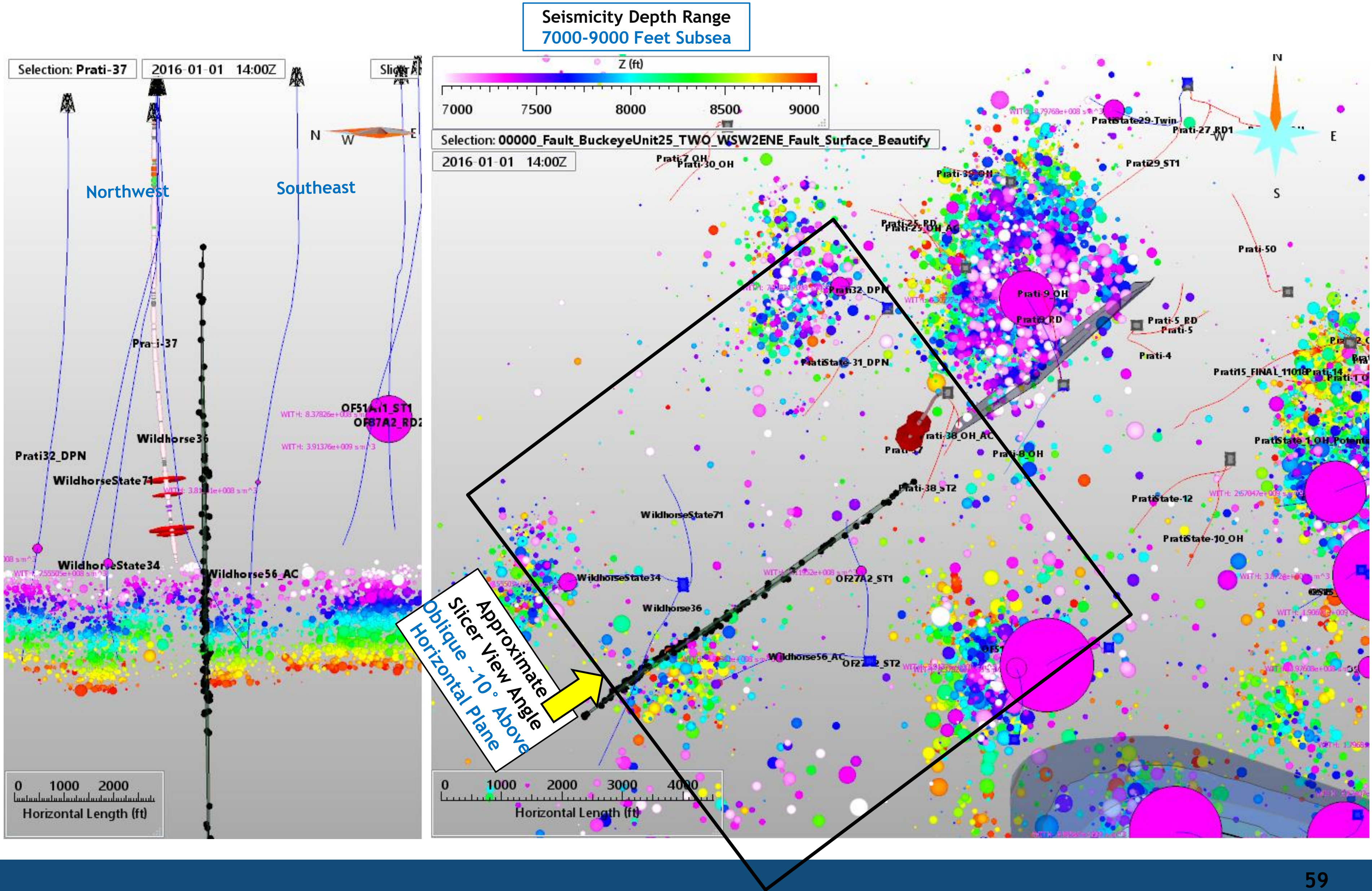
Interpreted Fracture/Fault Zones Assessment



Seismic Monitoring Advisory Committee Meeting
Interpreted Fracture/Fault Zones Assessment



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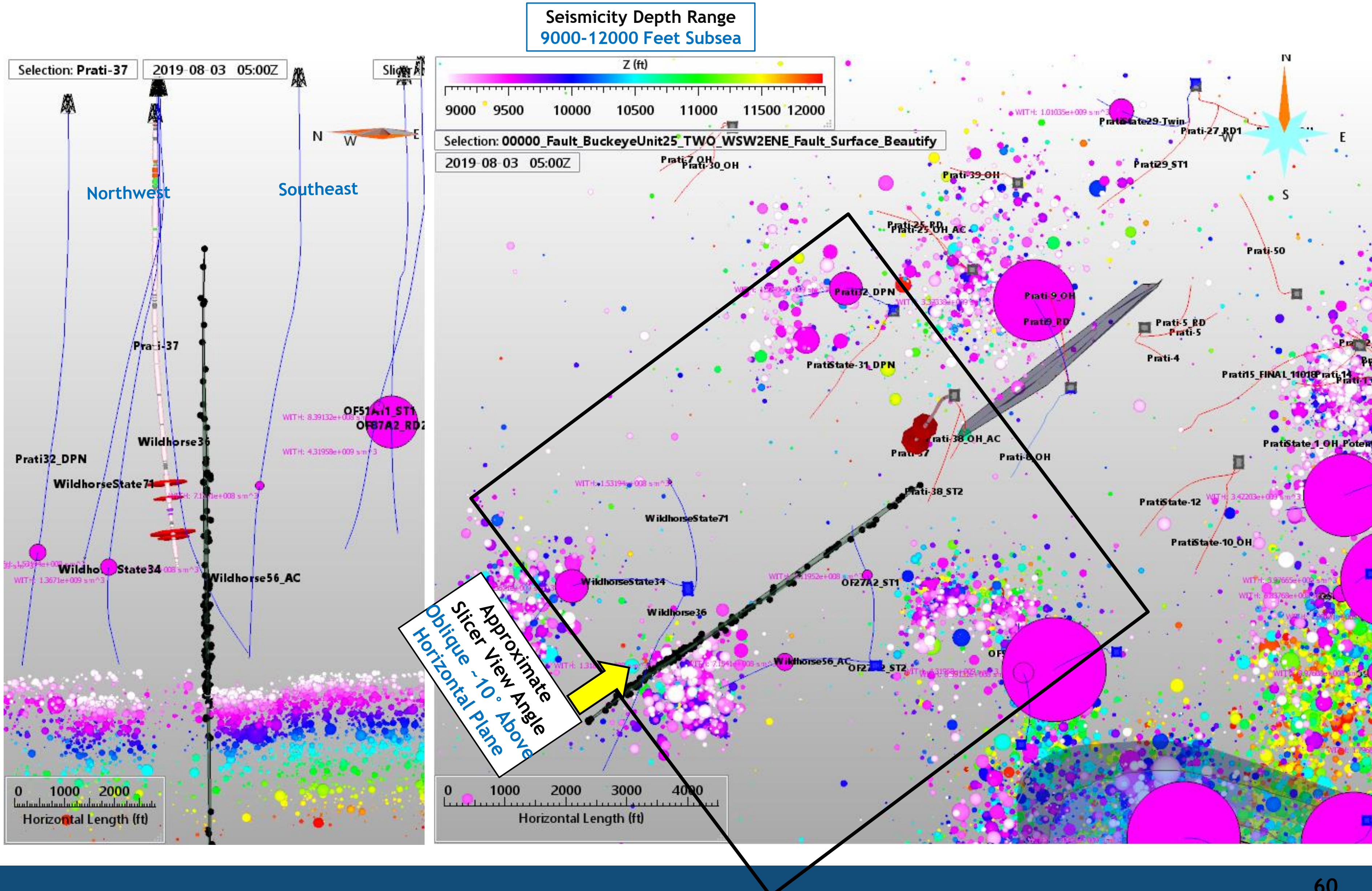
Interpreted Fracture/Fault Zones Assessment



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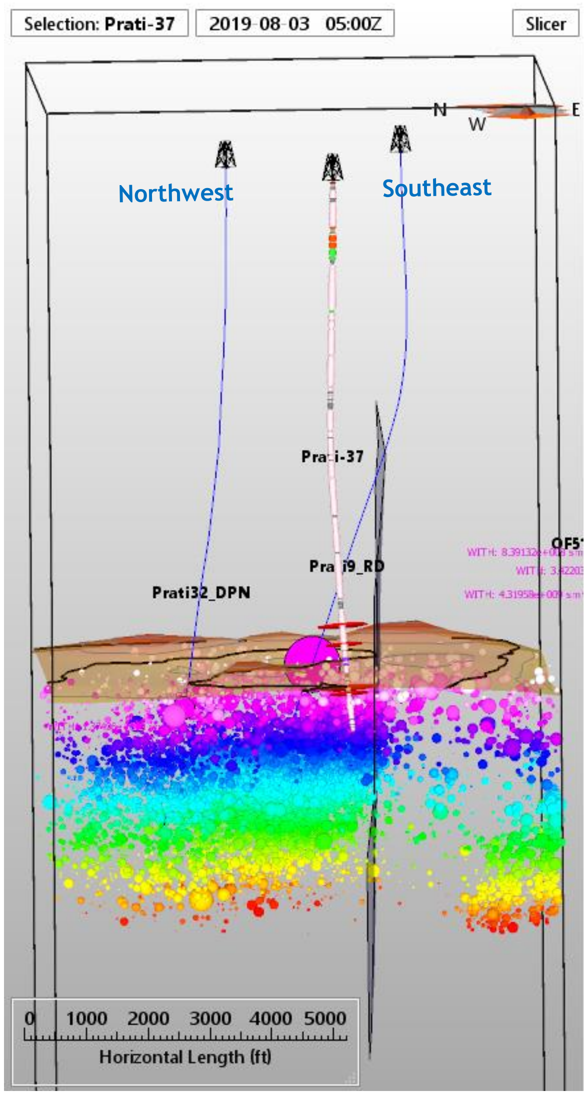
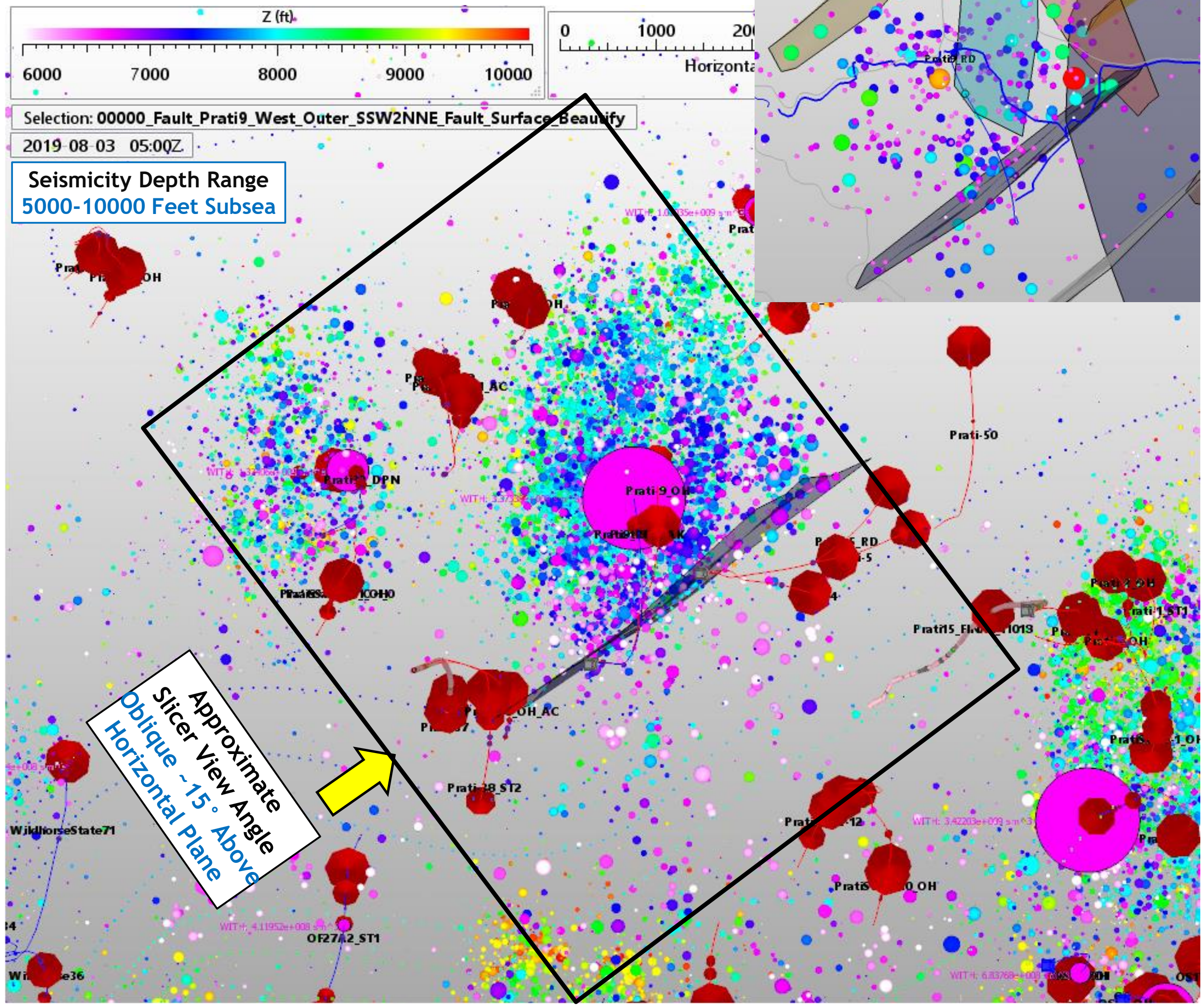
Interpreted Fracture/Fault Zones Assessment

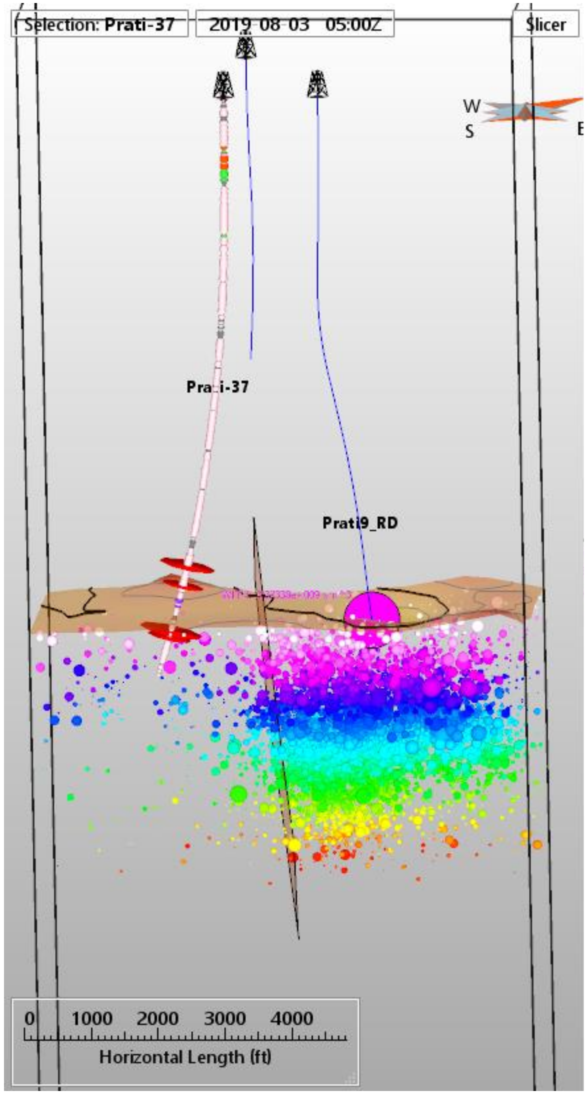
Induced seismicity appears to strongly define a reservoir compartment receiving Prati 9 water injection. The relationship between relatively high volume water injection, compartmentalization, and a 03 July 2019 magnitude 3.18 seismic event occurring near an interpreted fault-fracture surface is being investigated.

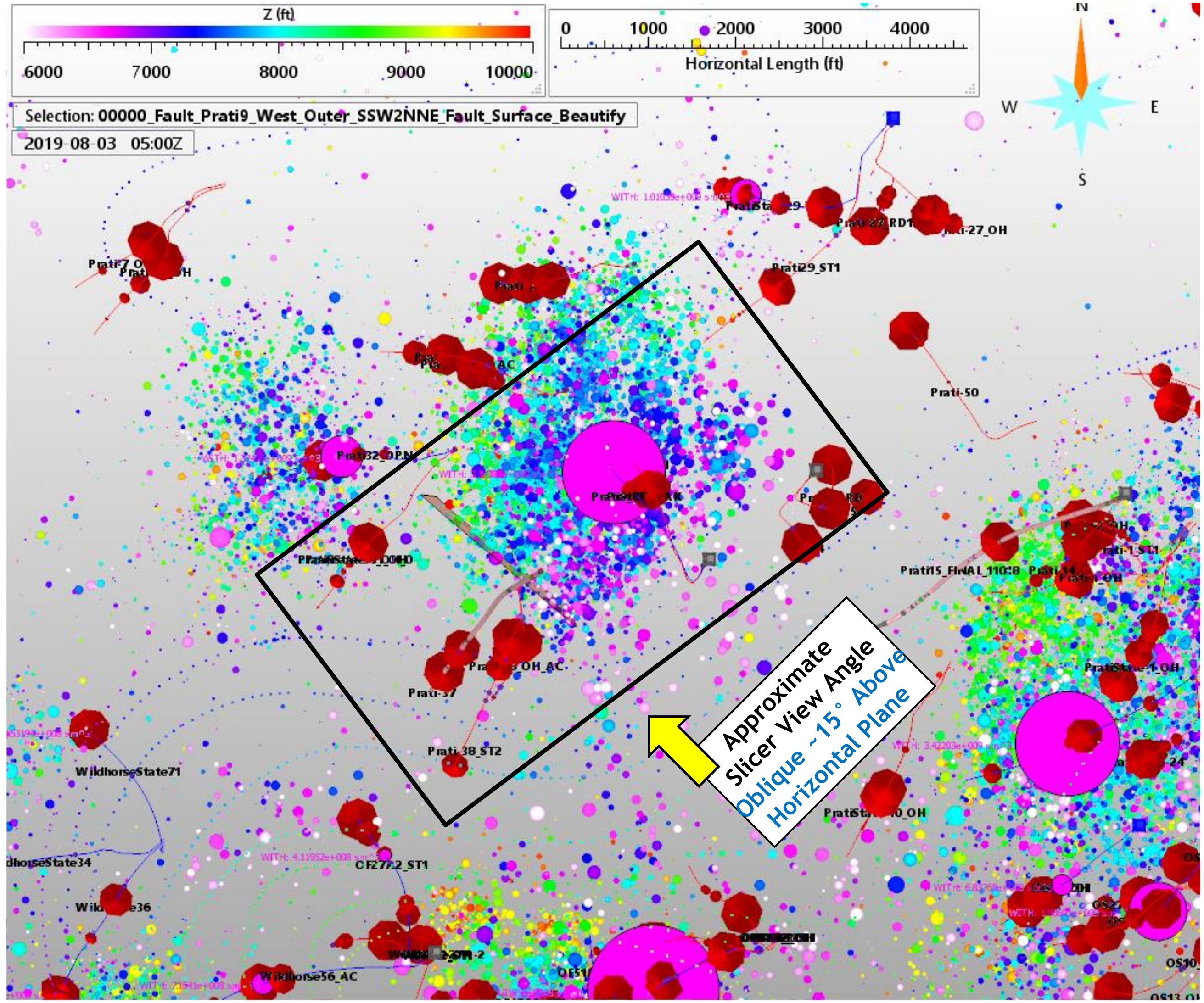




Seismic Monitoring Advisory Committee Meeting

Interpreted Fracture/Fault Zones Assessment





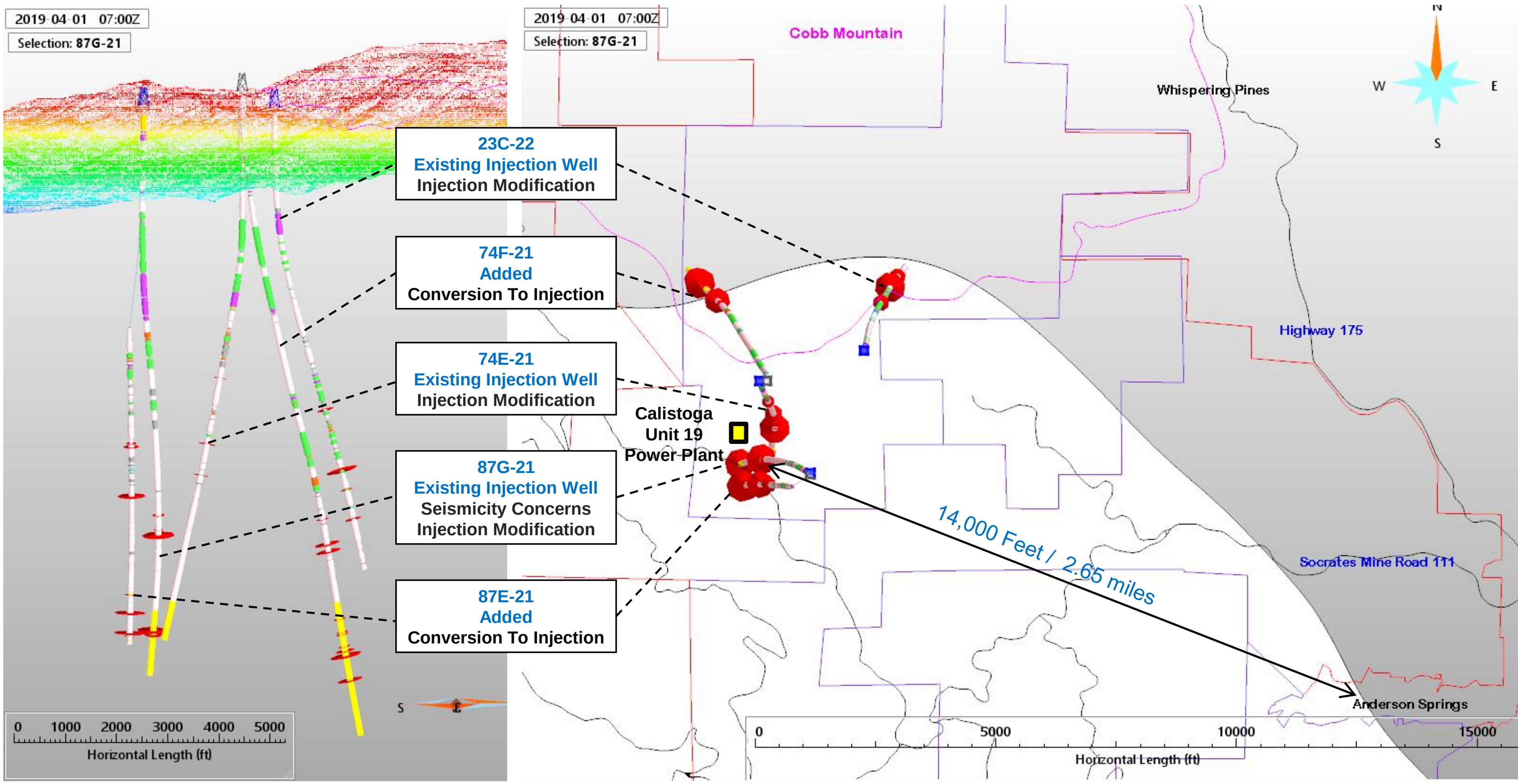
Seismic Monitoring Advisory Committee Meeting

Improved Water Distribution for Seismicity Mitigation

Conversion-To-Injection Drilling Program COMPLETED

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



Seismic Monitoring Advisory Committee Meeting
Additional Seismic Monitoring and Research
California Energy Commission Electric Program Investment Charge (EPIC) Program EPC-16-021

Accepted Proposal

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

Program Goal

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

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

Applicant

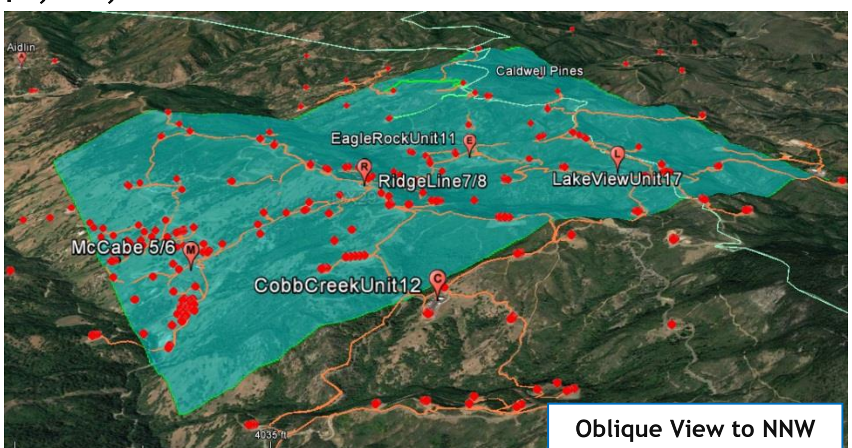
Lawrence Berkeley National Laboratory

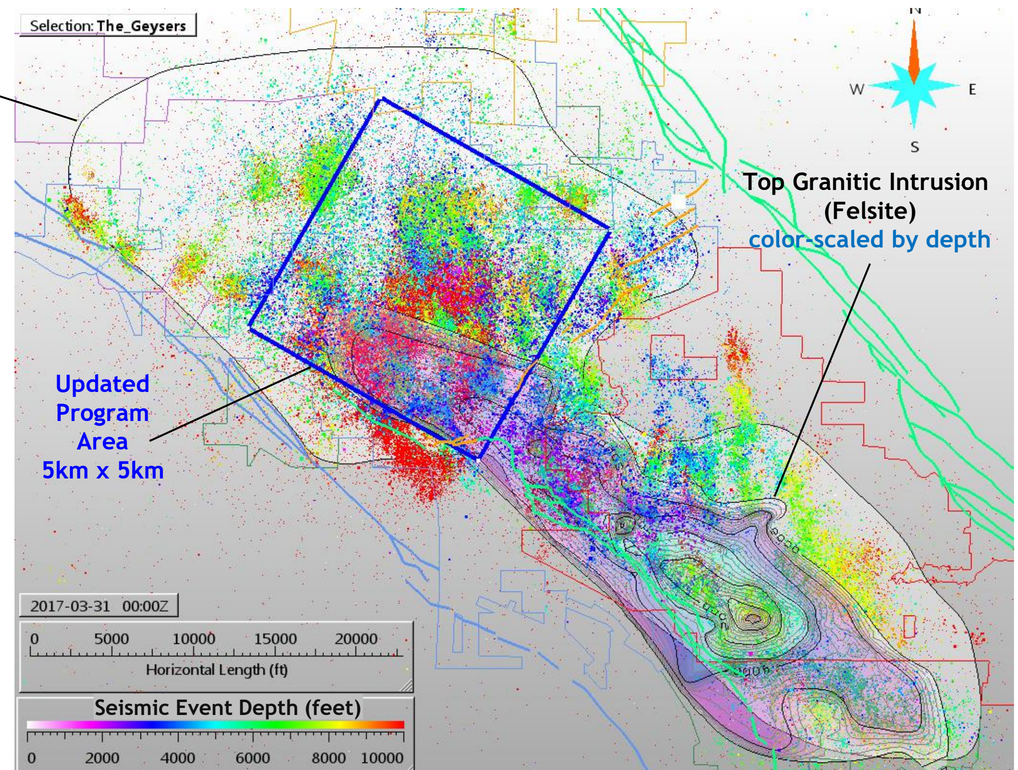
Project Partners

Calpine Corporation
Array Information Technology

California Energy Commission Funds Recommended

$1,672,639





Seismic Monitoring Advisory Committee Meeting

Additional Seismic Monitoring and Research

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

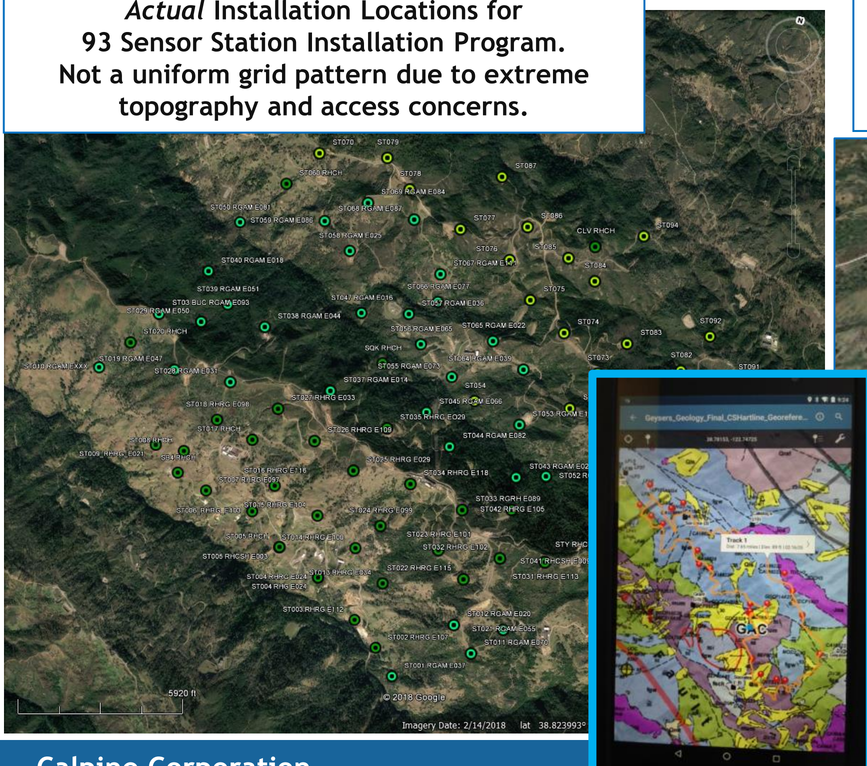
An extensive seismic sensor test program was planned and is being conducted with the project scientists.

Calpine Corporation has provided:

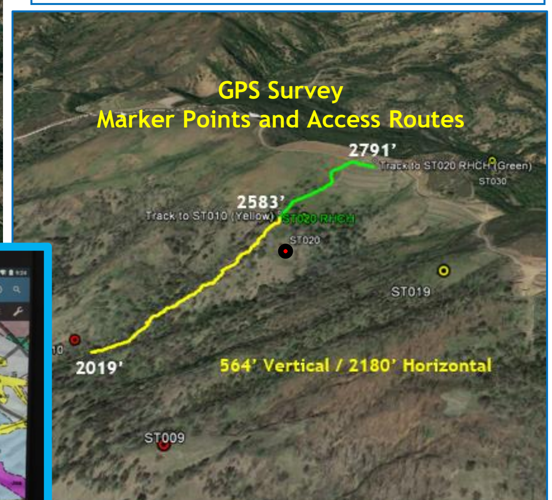
- The field location for this program.
- Technical support with survey design planning.
- On-site assessments including GPS surveying with updated equipment and techniques.
- Assistance to LBNL Contractor Ramsey Haught during 17 seismic sensor test installations.
- Coordination and updating of GPS surveys/maps data recovery at 2-3 month intervals.

Generation Three Sensor Station

Green Labeled Points
Actual Installation Locations for
93 Sensor Station Installation Program.
Not a uniform grid pattern due to extreme topography and access concerns.



Surveying of 23 Test Sensor Station Locations and Access Routes Completed By Calpine With Samsung Nexus 7 Tablet and Paired Garmin GLO Device.



Sensor Installation on Rock Outcrop

High-Resolution Imaging of Geothermal Flow Paths Using a Cost-Effective Dense Seismic Network

R. Gritto[1)], S. Jarpe[2)], M. Schoenball[3)], C.S. Hartline[4)], L.J. Hutchings[2)], K.T. Nihei[3)], C. Ulrich[3)]
[1)]Array Information Technology, , [2)]Jarpe Data Solutions, [3)]Lawrence Berkeley Nat. Lab, [4)]Calpine Corp.

ARRAY Information Technology
CALIFORNIA ENERGY COMMISSION

1. Abstract

The goal of this paper is to present the advantages of using cost-effective dense seismic networks to image the reservoir structure and flow paths at The Geysers geothermal reservoir in northern California, USA. The project employs 91 three-component 4.5 Hz geophones, spaced at approximately 500 m over a 5 x 5 km study area. Seismic data for more than 17,000 earthquakes, over a period of one year, were acquired and automatically processed for P- and S-wave phase arrival times. The data were subsequently inverted for the 3D P- and S-wave velocity structure and hypocenter locations. While the full dataset yields the highest resolution in the study region and represents the best opportunity to image flow paths and the 3D structure of the reservoir, temporal changes are best imaged by subdividing the dataset into several epochs and by determining temporal differences in the results. Tomographic images will be appraised by integration into The Geysers' 3D reservoir model and by spatial correlation to injection and production wells. The advantage of using the high-density seismic network are assessed by comparison to results obtained with lower-density seismic networks that are typically deployed in geothermal reservoirs.

2. Methodology

Seismic data processing is performed by Jarpe Data Solutions (JDS), based on the REMAS software, which provides complete data processing including phase detection, preliminary event location, estimation of phase travel time, pulse width, event moment magnitude, seismic moment, generation of waveforms and storage of parameters in database. The seismic tomographic imaging is based on the inversion code tomoFDD, which simultaneously locates earthquakes in an absolute and double-difference sense and to obtain 3D P- and S-wave velocity structure (Gritto et al., 2013). The 3D P- and S-wave starting velocity model for the tomographic inversion was taken from Gritto et al. (2013), while the node spacing was 150 m in each direction. The first inversion was conducted with data for the time period May 2018 to June 2019, which consisted of more than 17,000 preliminary event locations with over 634,000 P-wave and 595,000 S-wave phase arrivals. The time-lapse imaging was performed with two datasets, the first from May 2018 to December 2018 and the second from January 2019 to June 2019. Each dataset consisted of more than 2,780 events that were co-located within a limit of 150 m (one Fresnel zone of the S-wave) and contained the same P- and S-wave picks from each event pair recorded by the same seismic station. This selection guarantees equal sampling of the reservoir between the two datasets, within the spatial sensitivity of one S-wavelength. Finally, we conducted a comparative study to image the study area based on the station density of the permanent Geysers seismic network, which is more representative of networks operating in other geothermal reservoirs.

3. Seismic Network

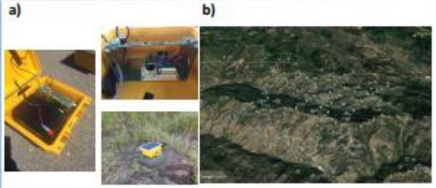


Figure 1: **a)** Seismic sensors used in the dense network deployment at The Geysers geothermal reservoir. The sensors consist of three orthogonally oriented 4.5 Hz geophones, 24-bit digitizer, 10 W solar panel, 12 V battery, GPS antenna, and two SD memory card slots. **b)** Final deployment of the 91-station seismic network in a 5 km x 5 km study area at The Geysers geothermal reservoir, CA.

4. Seismic Imaging

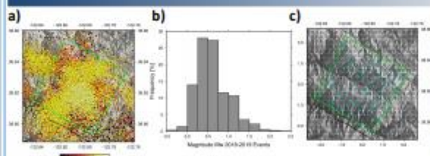


Figure 2: **a)** Spatial distribution of 17,000 events recorded over a one-year period from May 2018 to June 2019. The green square denotes the outline of the study area of the current project. **b)** Histogram with magnitude distribution for events shown in a). **c)** Black dots denote the nodes (150 m spacing) used for the tomographic inversion of the seismic data. The teal-colored triangles represent the dense 91-station seismic network.

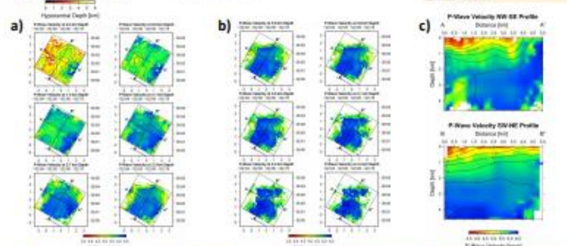


Figure 3: **a)** Map view of P-wave velocity estimates in the 5 km x 5 km study area of The Geysers geothermal reservoir. **a)** Horizontal slices from 0.3 km to 3.3 km depth. The velocity estimates are only displayed for areas that are resolved with respect to the derivative weight sum (DWS). **b)** Same as a) for horizontal slices between 3.6 km and 4.4 km depth. **c)** P-wave velocity estimates for the vertical cross sections labeled A-A" and B-B" in a) and b).

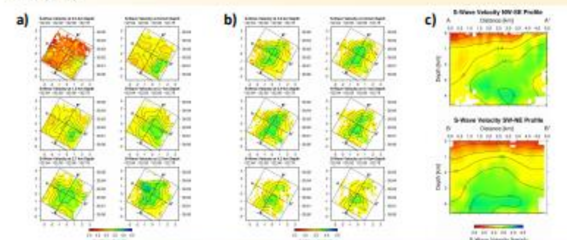


Figure 4: **a)** Map view of S-wave velocity estimates in the 5 km x 5 km study area of The Geysers geothermal reservoir. **a)** Horizontal slices from 0.3 km to 3.3 km depth. The velocity estimates are only displayed for areas that are resolved with respect to the derivative weight sum (DWS). **b)** Same as a) for horizontal slices between 3.6 km and 4.4 km depth. **c)** S-wave velocity estimates for the vertical cross sections labeled A-A" and B-B" in a) and b).

5. Time-Lapse Imaging

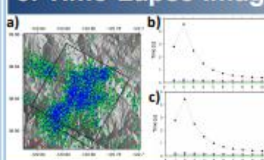


Figure 5: **a)** Spatial distribution of two sets of 2,780 "co-located" event pairs that were recorded between May 2018 and December 2018 (blue dots) and between January 2019 and June 2019 (green dots). The "co-located" event pairs have a maximum separation of 150 m each, representing one Fresnel zone of the S-wavelength. The maximum separation assures that the respective waves, propagating from the hypocenters to the recording stations, sample the same region of the reservoir in both data sets. The events were subsequently used for time-lapse seismic imaging of temporal changes in the reservoir. **b)** Time-misfit curve as a function of iteration for the 2018 data set. black: weighted variance, green: absolute variance, blue: weighted mean, red: absolute mean. **c)** Same as b) for the 2019 data set. The similarity of the curves results from the same regularization of the two data sets in the separate inversion runs.

5. Time-Lapse Imaging Cont.

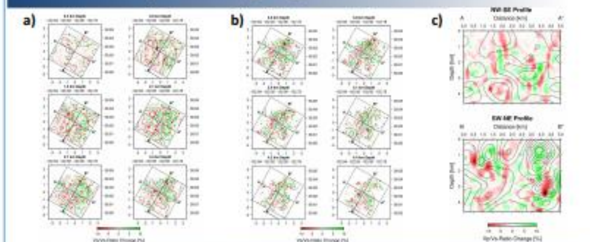
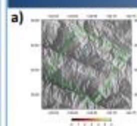


Figure 6: Map view of the temporal changes in Vp/Vs-ratio in the 5 km x 5 km study area of The Geysers geothermal reservoir. **a)** Horizontal slices from 0.3 km to 3.3 km depth. The Vp/Vs-ratio estimates are only displayed for areas that are resolved with respect to the derivative weight sum (DWS). **b)** Same as a) for horizontal slices between 3.6 km and 4.4 km depth. **c)** Vp/Vs-ratio estimates for the vertical cross sections labeled A-A" and B-B" in a) and b). The temporal changes in Vp, Vs and Vp/Vs estimates obtained from time-lapse imaging will be incorporated into a 3D reservoir model and spatially correlated to changes in water injection and steam production to guide reservoir operations (see Section 6 below).

6. Network With Lower Station Density



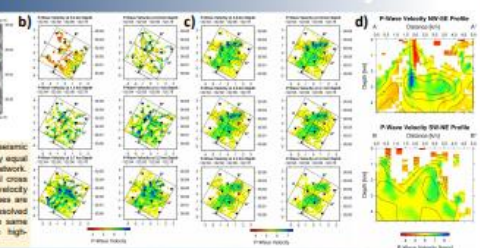


Figure 7: **a)** Assumed seismic network with stations density equal to the permanent Geysers network. **b)-d)** Horizontal and vertical cross sections of the P-wave velocity estimates. The velocity values are overestimated and poorly resolved when attempting to use the same node spacing as for the high-density network in Figure 3.

7. Future Work (Rock Physics)

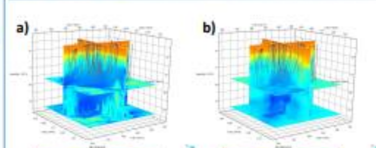


Figure 8: Fence diagrams of velocity estimates in the 5 km x 5 km study area. The velocity estimates and data from The Geysers 3D reservoir model are imported into SKUA-GOCAD to aid with the interpretation of the seismic imaging results. The trajectories of injection (deeper) and production (shallower) wells are superimposed on the velocity estimates. **a)** P-wave velocity estimates. **b)** S-wave velocity estimates. Note the pulldown of lower P-wave velocities (orange) in the shallow subsurface in the vicinity of steam production wells and the higher P-wave velocities (blue) below the water injection wells at depth. These spatial correlations are less apparent in the S-wave velocities.

8. References and Acknowledgement

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Graphics were generated using the Generic Mapping Tools (www.soest.hawaii.edu/gmt: Wessel and Smith, 1998).

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The authors would like to thank Calpine Corporation for access to the field, Ramsey Haught for his help in testing and installing the seismic sensors and Florian Soom for collecting the seismic data in the field.

Additional Seismic Monitoring and Research

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

EARTH & ENVIRONMENTAL SCIENCES

In-depth Analysis from Deployments of Low-Cost Seismic Instruments in the Geysers Geothermal Field

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ABSTRACT

The Geysers Geothermal field is the world's largest geothermal field with with a net generating capacity of about 725 MWe. Its first power plant went into operation in the early 1960s. The seismicity has been monitored with a local network for the past 40 years and is well studied.

This study is part of an effort to develop a low-cost seismic imaging system that uses micro earthquakes to form high spatial and temporal resolution images of subsurface fluid flow, flow barriers and heterogeneity in geothermal environments. The study uses low-cost seismic instruments that allow the deployment of a dense seismic network at a fraction of the cost. The study area has an extent of 5 by 5 km, and is located in the central part of the reservoir.

In this presentation, we show an in-depth comparison between the temporary network of low-cost stations and the permanent seismic stations that have been deployed at The Geyser for the past 10 years. Out of 91 temporary stations, five were co-located with stations of the permanent network.

First, we analyze the statistical parameters of the seismic catalogues recorded by each network during different deployment periods. We present changes in the b-values and the magnitude of completeness over time and space and interpret the changes. Second, we use local events between magnitudes M0.5 and M2.5 to emphasize the differences, and, more importantly the similiarities between the co-located stations. We compare the waveforms and their spectral character to highlight the performance of the low-cost stations.

BACKGROUND

The Geysers Geothermal Field (GGF) is in Northern California within a dense fault network (Fig 1). Over 30'000 micro earthquakes are recorded by a dense local network (Fig 2) each year.

The spatial and temporal evolution of the micro-seismicity, together with injection and production data and the geologic information is used to gain information about the movement of the fluid and steam in the subsurface.

Fig 1: The regional setting of the GGF (Hartline et al, 2015)

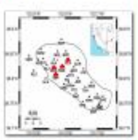


Fig 2: Permanent seismic network at The Geysers (Viegas and Hutchings, 2010).

OBJECTIVES

- How to image presence and movement of water and steam reliably and cost effectively
  - Wells are expensive (up to $7M/well)
  - Micro-seismicity alone might not be a direct proxy for presence and flow of water (presence of micro-seismicity due to stress alone, aseismic movement of fluids)
- ➢ Low-cost seismic instruments allow dense arrays
  - ~100 stations in a 5 km by 5 km area
- ➢ High resolution tomographic imaging
  - See Poster: **"S11F-0393 - High-Resolution Imaging of Geothermal Flow Paths Using a Cost-Effective Dense Seismic Network"**

SEISMIC INSTRUMENTS

Size	25x25x10 cm
Weight	4 kg
Input Voltage	10-16 VDC
Solar Panel	not tilting, 10 W
Power Consumption	360 mW
Sensors	4.5 Hz, HGS, HG6-HS
Data Conversion	Delta-sigma, 24 bit
Channels	3
Sample Rate	200 sps(fNY=100 Hz)
Time Base	GPS (internal antenna)
GPS Accuracy	1 ms
Recording	continuous
Output	SD Memory Card (2 slots)

Table 1: Specifications of the seismic instruments

Fig 3: Location of the deployed stations; a total of 91 stations are deployed, five of which co-located with stations of the permanent BG network (inset table and red triangles indicate location of co-located stations)

FIELD DEMONSTRATIONS

Data collection campaigns were conducted on a quarterly basis

- This study includes data recorded between May to October 2018
  - Over 6000 events were detected and located with the temporary array
  - 1200 of these events can be correlated to events recorded by the permanent network

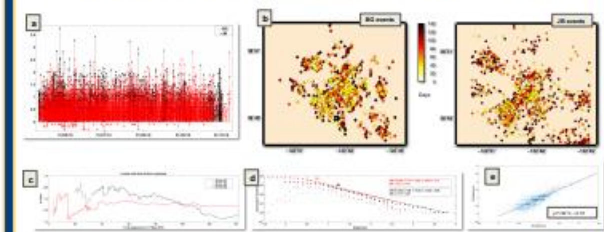


Fig 4: Statistics of seismic events recorded by the temporary (red / circles) and permanent network (black / diamonds): **a)** timeline, **b)** locations, **c)** b-value with time, **d)** frequency magnitude distribution and **e)** correlation of network magnitudes

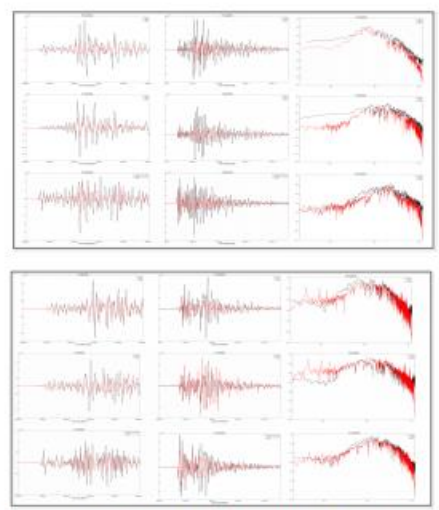


Fig 5: Waveforms from two events with magnitude M1.0 (May 28) and M 2.4 (August 24) recorded by two co-located stations (top: SQK / S46, bottom: BUC / S30). Spectra displayed for the M2.4 event only.

DISCUSSION

Earthquake statistics

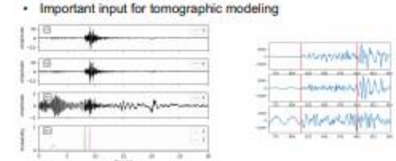
- Dense network locates three times more events (6000 vs. 2000)
- Magnitude of completeness smaller for dense network (M_c 0.5 vs M_c 1.0)
- b-value of dense network slightly smaller; less variation with time
- Dense network stations saturate for larger events

Sensor comparisons

- Waveforms between the temporary and permanent network show good agreement for the co-located stations
- While the maxima of the spectra match well, there is a larger disagreement in the lower and higher frequency range
  - ➢ Low cost sensors perform comparable to permanent sensors
  - ➢ Cost-effective setup allows fast turnaround of tomographic results to image subsurface fluid flow, flow barriers and heterogeneity in producing geothermal fields

NEXT STEPS

- Use neural network method *PhaseNet* (Zhu and Berosa, 2018) to improve P and S arrival picks
  - Has potential to produce picks where other methods fail
  - Can be applied to continuous data
  - Important input for tomographic modeling



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