Calpine Geysers Water Injection Goals

Improve Injection Distribution

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

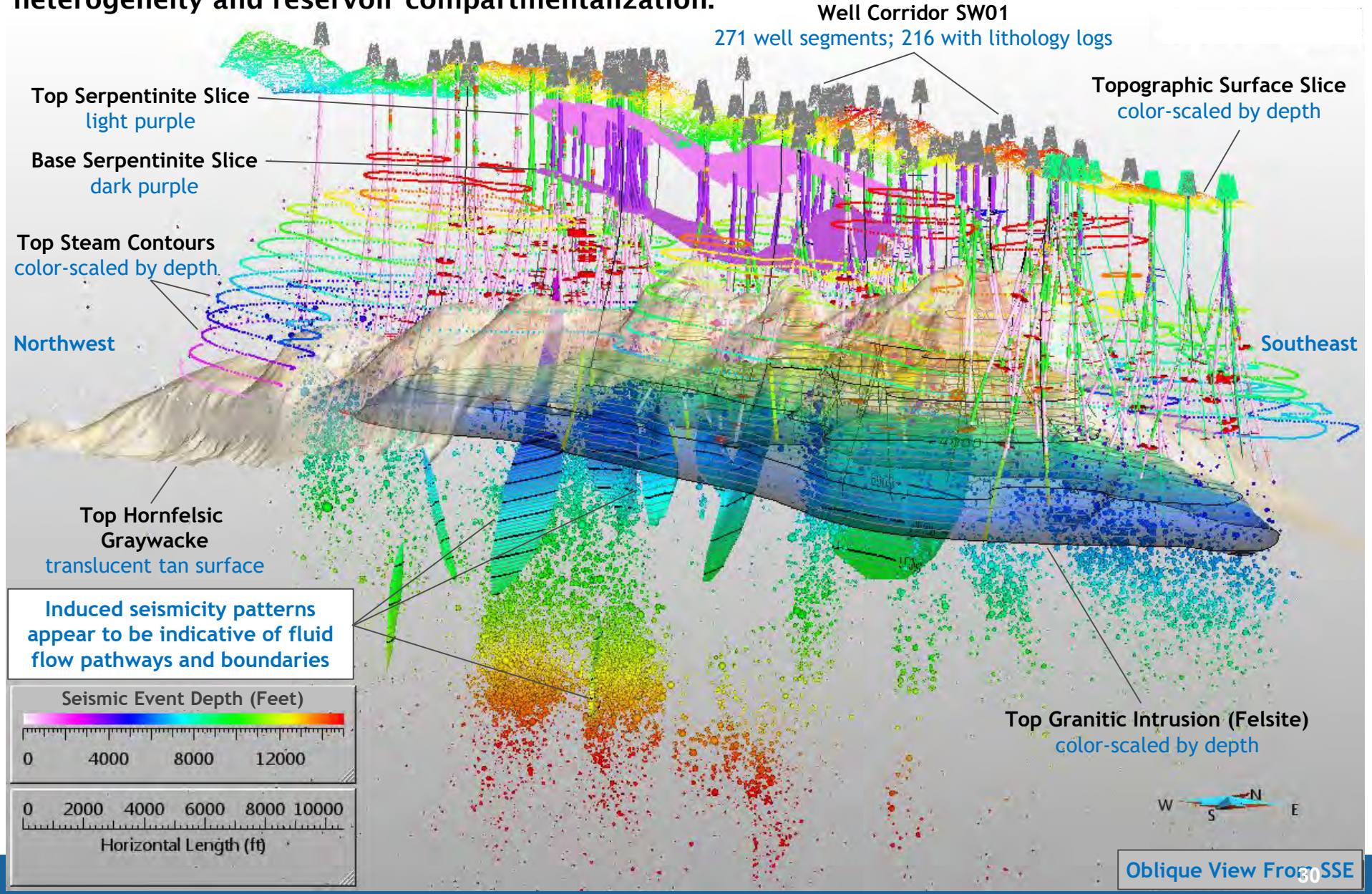
Minimize Injection Rate Variations

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

3D Structural Model Utilized For Recent Well Planning *and* Real-Time Drilling Analysis

Seismic Monitoring Advisory Committee Meeting

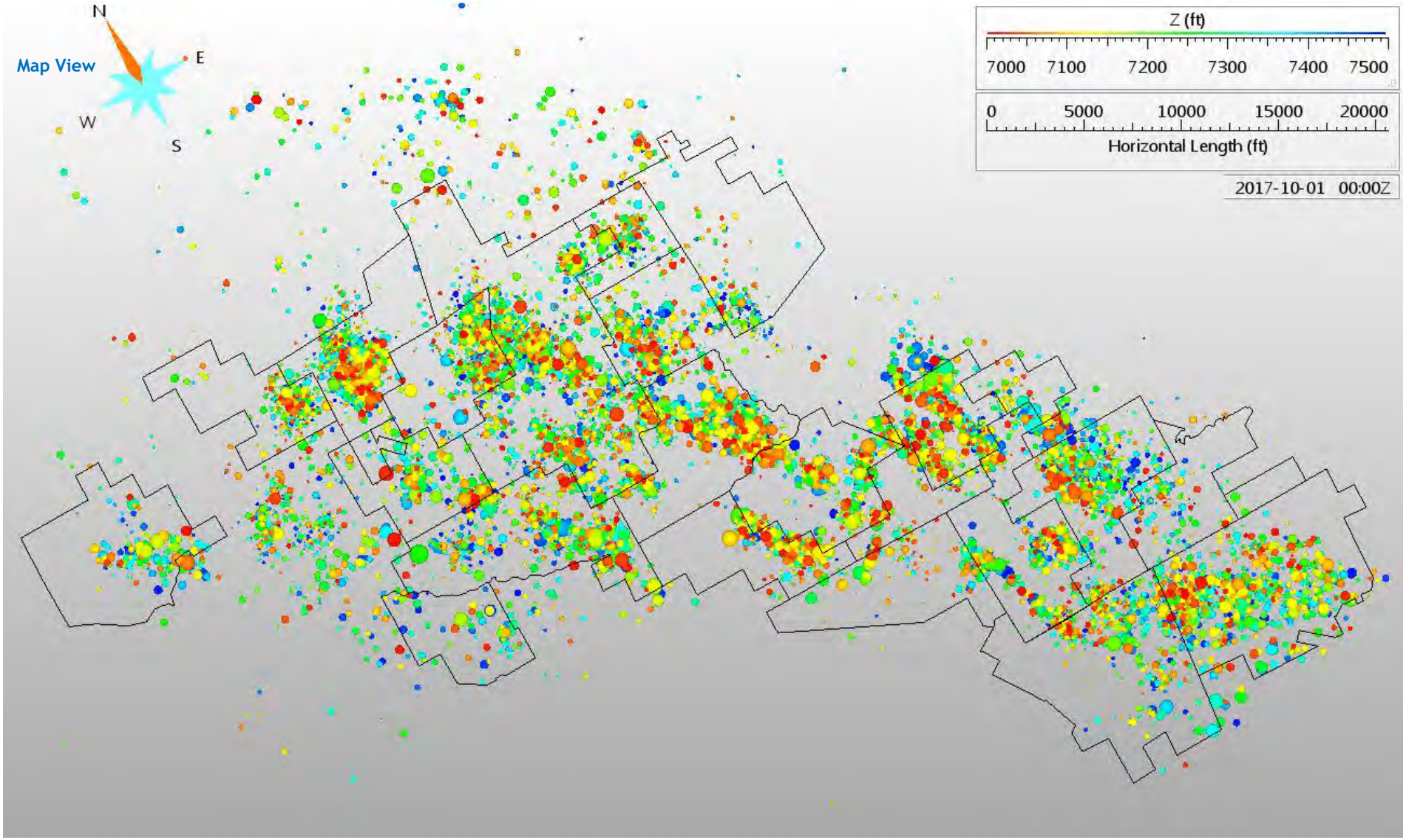
3D Structural Model Building Goal: Improved reservoir management and induced seismicity mitigation through a refined understanding of fluid flow paths, fluid boundaries, reservoir heterogeneity and reservoir compartmentalization.



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

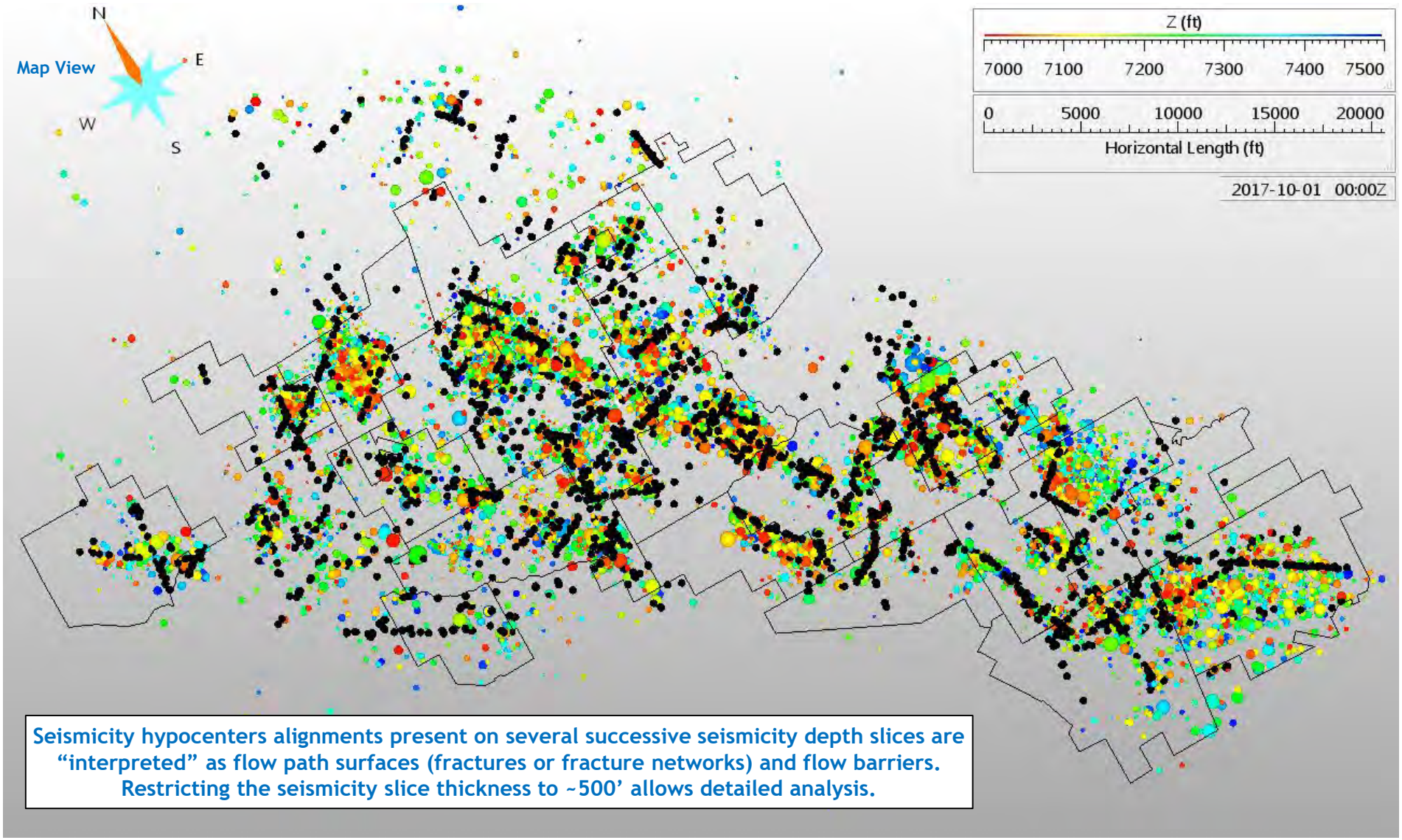
Depth Slice 7000 to 7500 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

Depth Slice 7000 to 7500 Feet Subsea

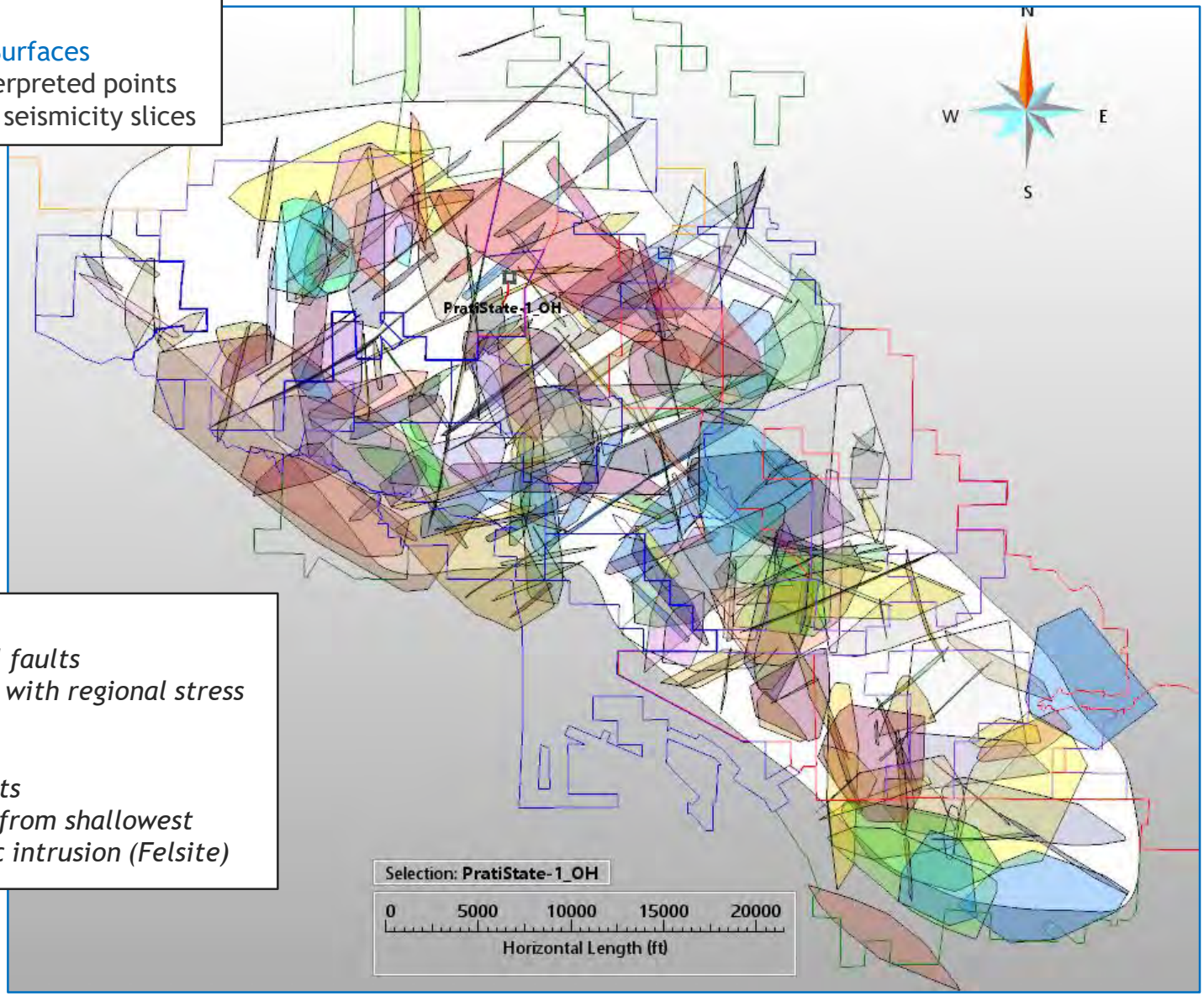


Seismicity hypocenters alignments present on several successive seismicity depth slices are "interpreted" as flow path surfaces (fractures or fracture networks) and flow barriers. Restricting the seismicity slice thickness to ~500' allows detailed analysis.

Prati State 1 OH Steam Production Well Recompletion

Fault/Fracture Interpretation With Seismicity Slices

By April 2018:
- 273 Refined Fault/Fracture Surfaces
- From 31,500 individually interpreted points
- Picked on variously-oriented seismicity slices

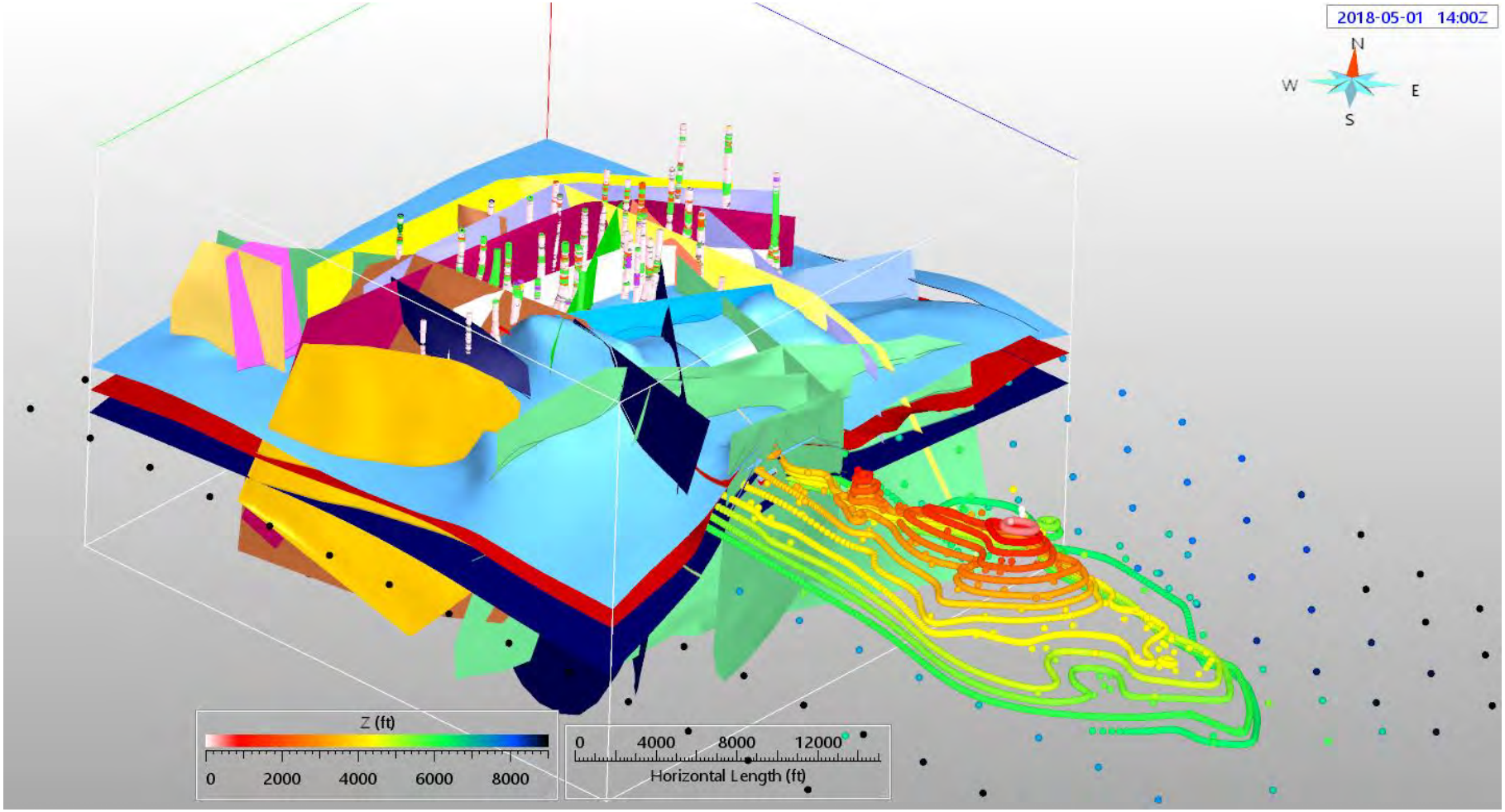


Northwest Geysers
Primarily near vertical faults
Orientation consistent with regional stress

Southeast Geysers
More non-vertical faults
Several faults radiate from shallowest penetration of granitic intrusion (Felsite)

Seismic Monitoring Advisory Committee Meeting

Structural Model Development – Northwest Geysers With Refined Fault/Fracture Interpretation



3D Structural Model Building: Oblique 3D view from south-southwest of the color depth-scaled Top Felsite contours and markers throughout the field, along with the faults and faulted horizons within the north Geysers test volume. Top Felsite points have been extended to the model boundaries base on the available lithological and seismicity constraints.

Seismic Monitoring Advisory Committee Meeting
Water Injection Well and Steam Production Well Modifications

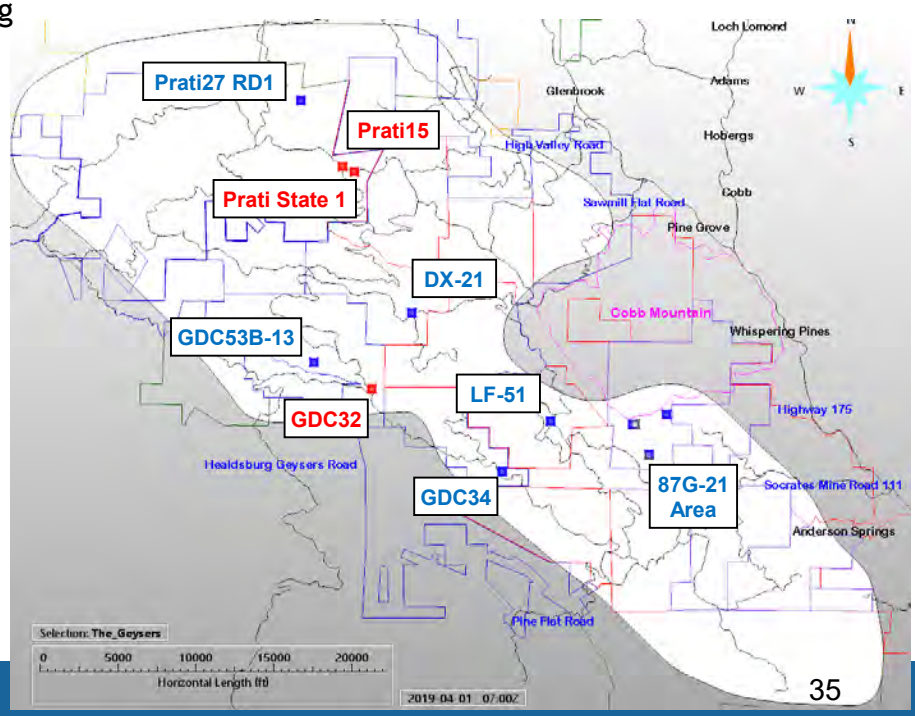
Water Injection

- **GDC34** November 2018 Drilling Completion
- **87G-21** Detailed Historical Seismicity Analysis Indicated:
  87G-21 Primarily Responsible for Magnitude ≥ 3.5 Seismicity in Calistoga Power Plant Area.
  Better Water Distribution Required for Seismicity Mitigation.
  - 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

  Program developed by experts in operations, drilling, and maintenance and resource management.
  Guidelines determined for water injection distribution into these five wells.
- **LF-51** November 2019 Drilling Initiation; Drilling Completion in 2020
- **DX-21** Spring 2020 Proposed Recompletion; 500' Deepening
- **GDC53B-13** Fall 2020 Proposed Drilling Initiation
- **Prati 27 RD1** 2021 Proposed Conversion To Injection

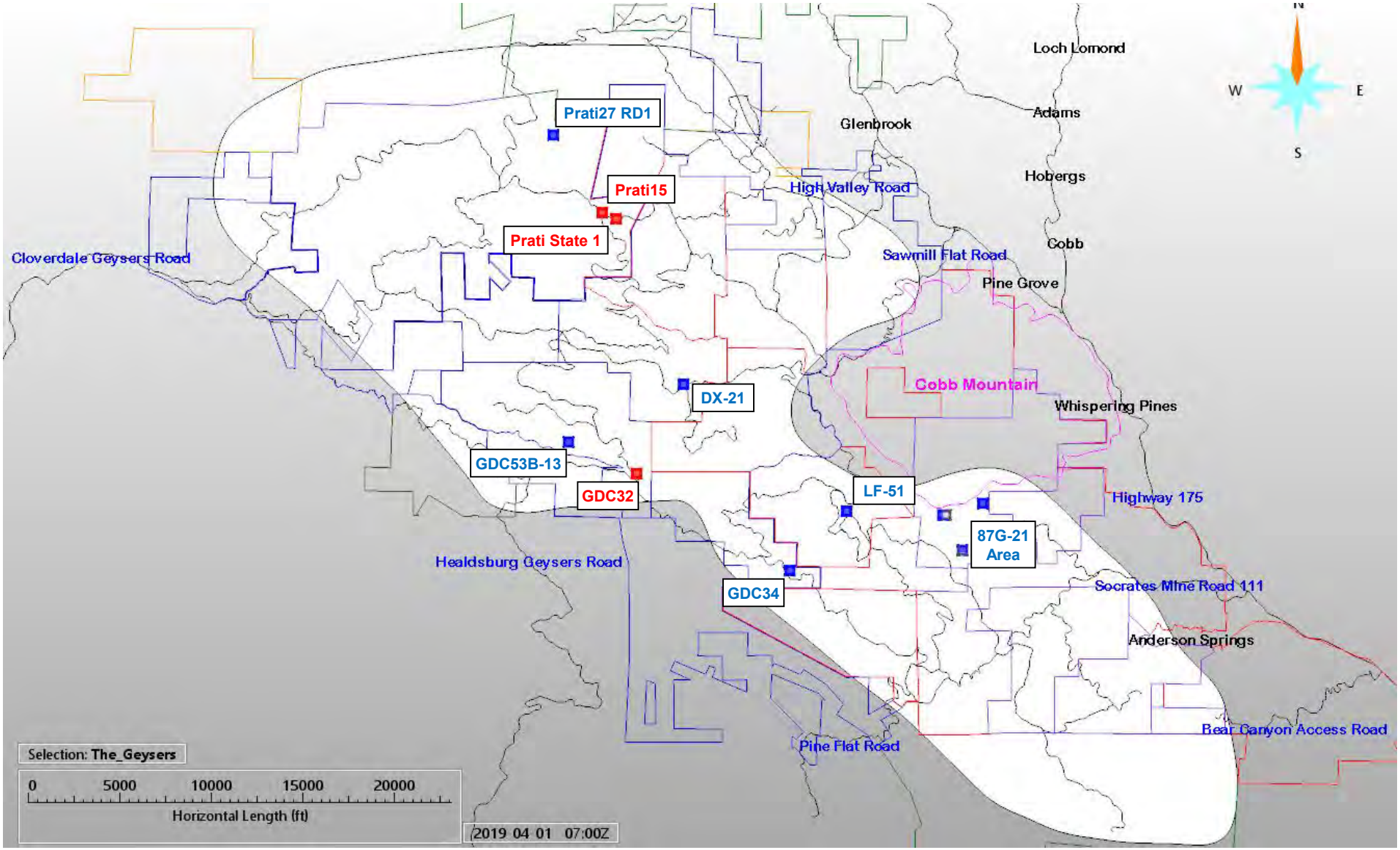
Steam Production

- **Prati 15** May 2019 Drilling Initiation
- **Prati State 1** Proposed Recompletion; Improve Steam Recovery
- **GDC32** 2020 Proposed Steam Production



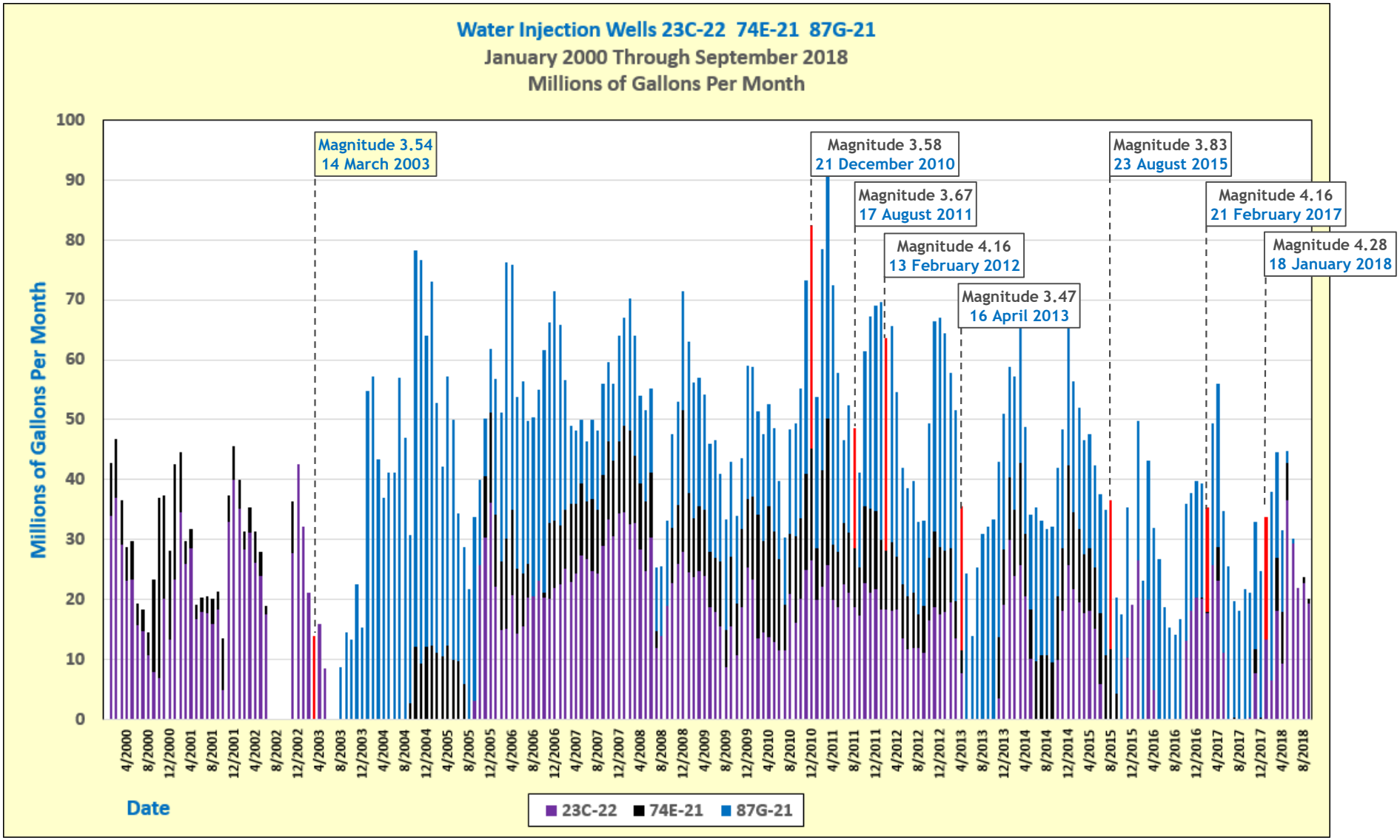
Seismic Monitoring Advisory Committee Meeting

Water Injection Well and Steam Production Well Reference Map



Seismic Monitoring Advisory Committee Meeting

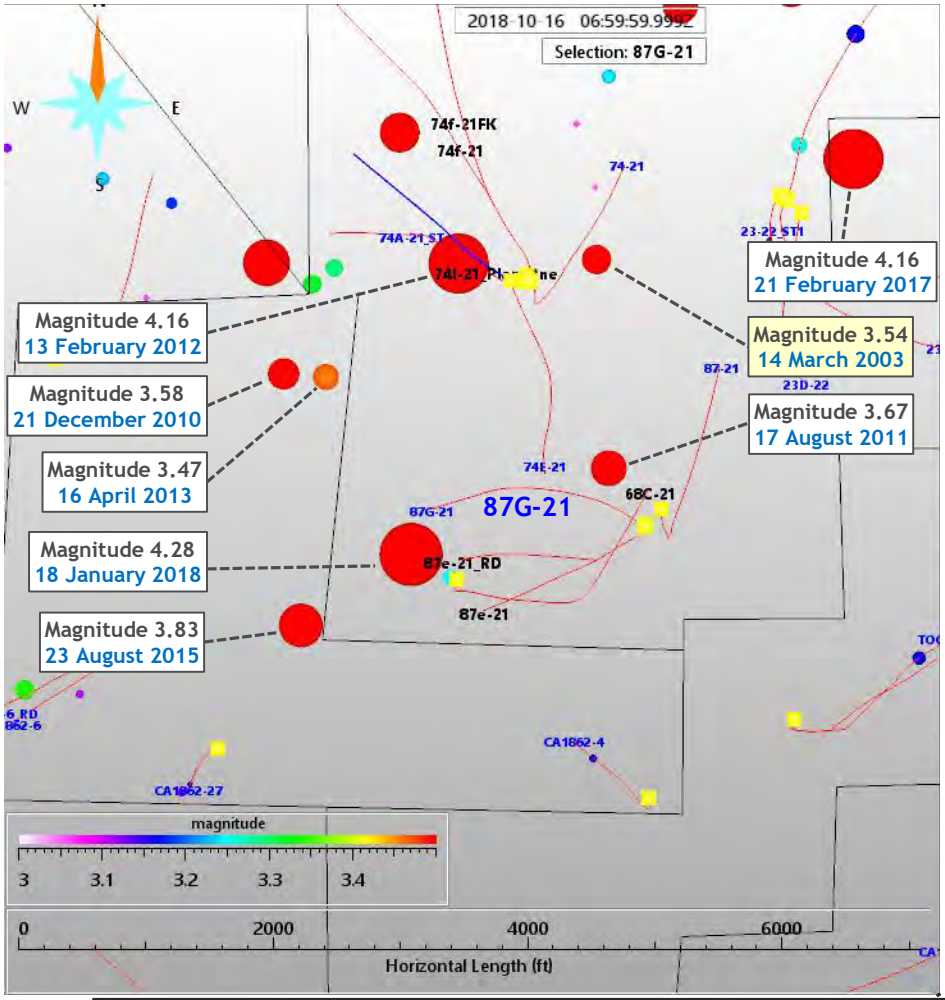
Calistoga Water Injection Wells 23C-22, 74E-21, 87G-21 and Seismicity in Vicinity



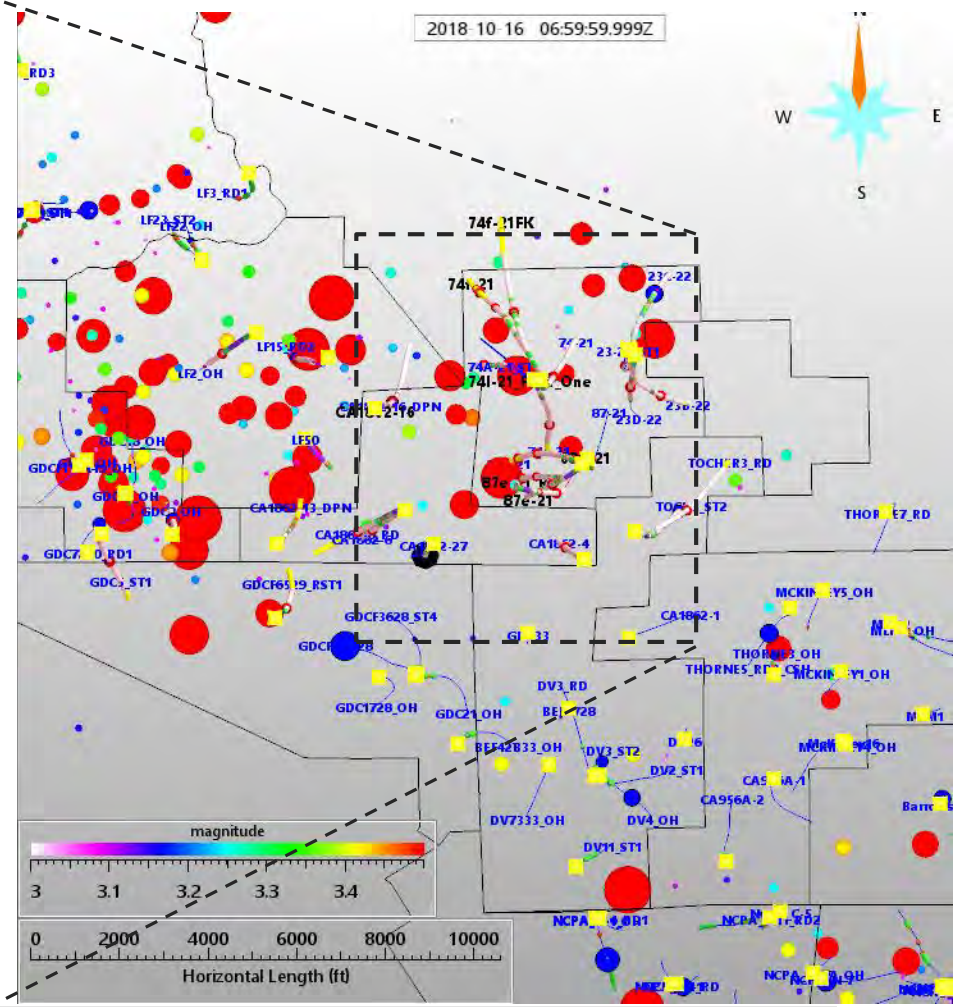
Seismic Monitoring Advisory Committee Meeting
Calistoga Area Water Injection and Seismicity Animation

Display Emphasizes Seismic Events Exceeding Magnitude 3.0

Map View (87G-21 At Center)



Map View

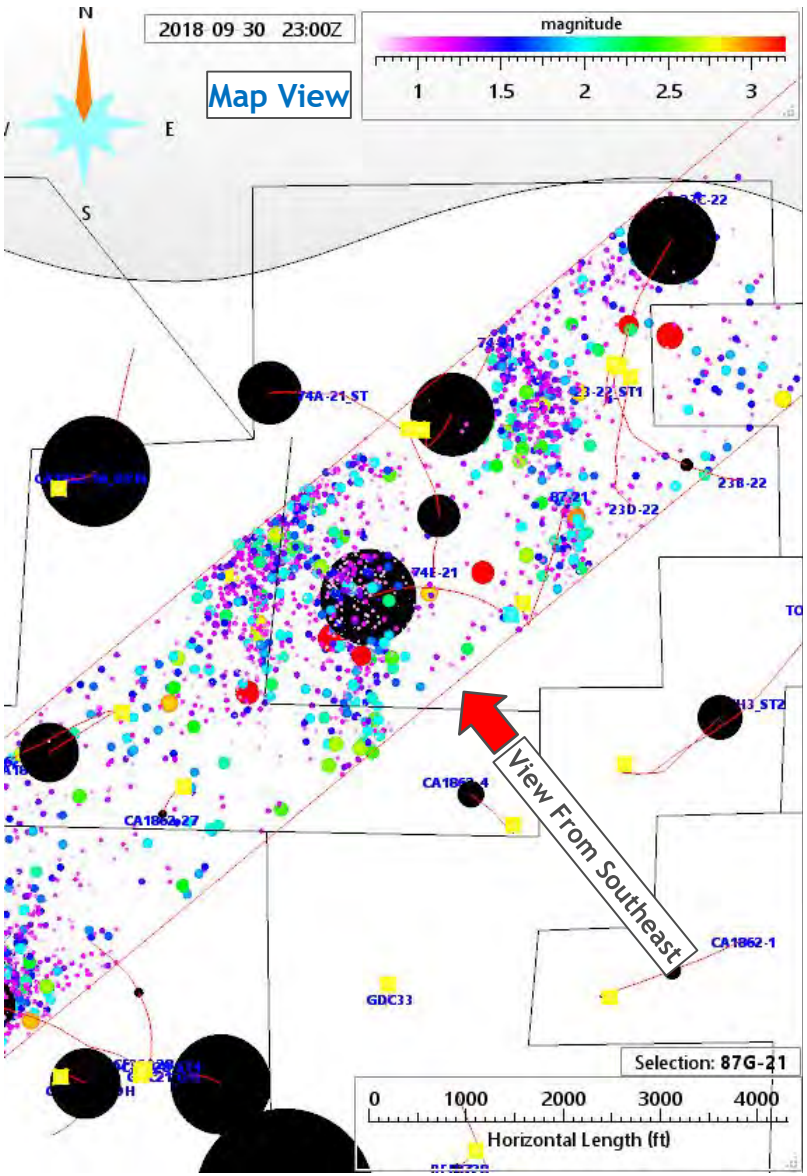


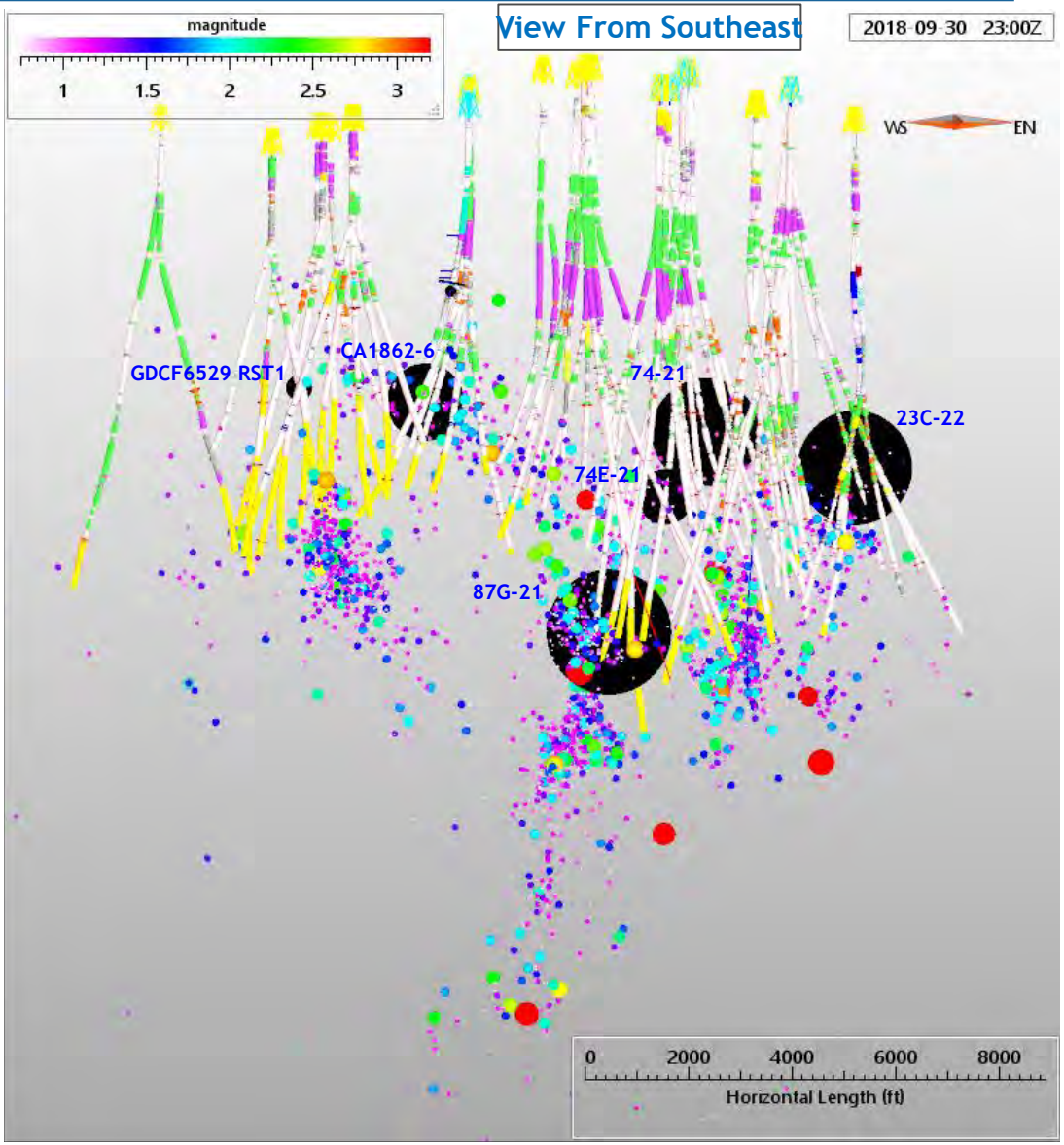
A detailed historical induced seismicity analysis in the vicinity of Calistoga water injection well 87G-21 suggest this well is primarily responsible for the occurrence of eight seismic events exceeding magnitude 3.5 since 2010.

Seismic Monitoring Advisory Committee Meeting

Calistoga Area Cumulative Water Injection and Induced Seismicity Animation

Relationship Between 87G-21 Cumulative Water Injection and Recent Induced Seismic Events Exceeding Magnitude 3.5

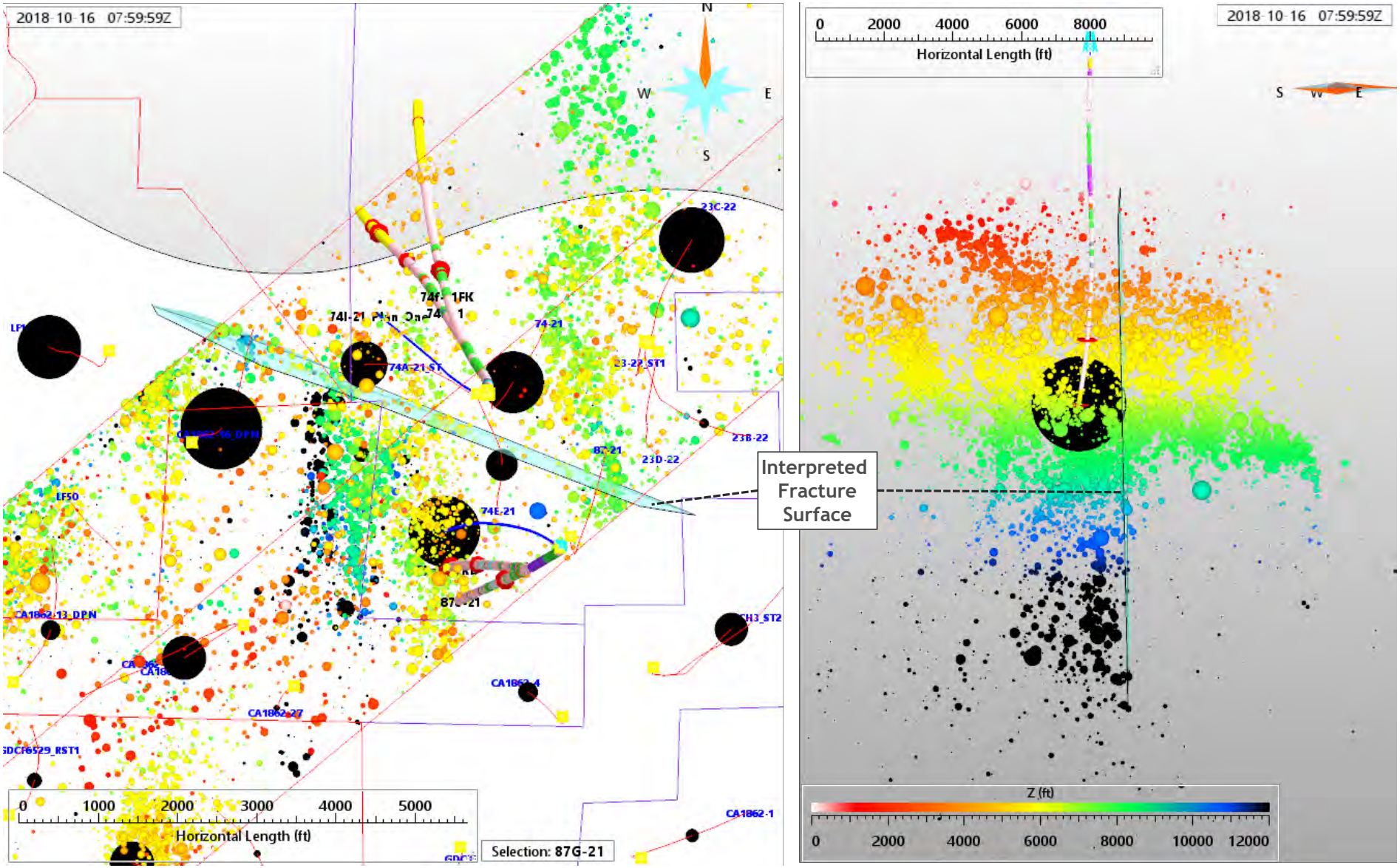




Seismic Monitoring Advisory Committee Meeting

Calistoga Area Fault/Fracture Interpretation With Seismicity Slice Animation

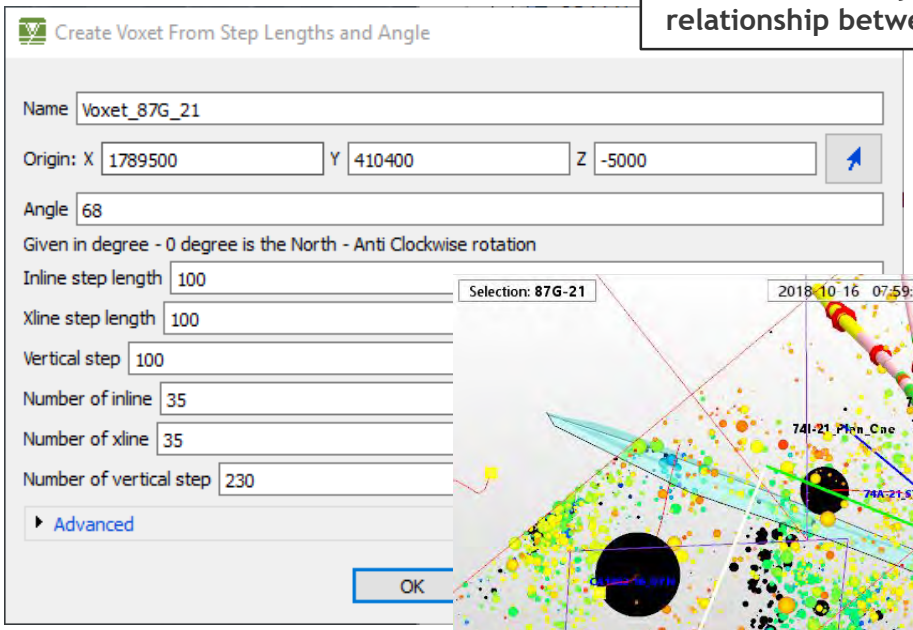
Induced seismicity patterns indicative of fluid flow pathways, fluid flow boundaries, reservoir heterogeneity and reservoir compartmentalization at The Geysers should contribute to improved reservoir management and induced seismicity mitigation.



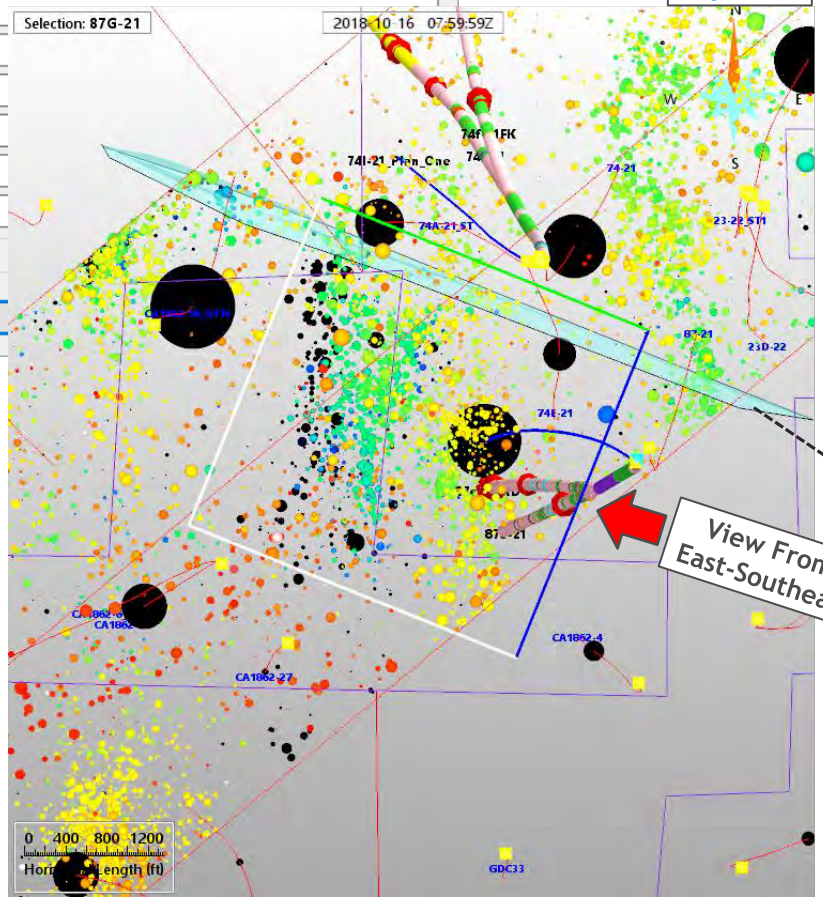
Seismic Monitoring Advisory Committee Meeting

Calistoga Area Microseismic Stimulated Reservoir Volume Analysis

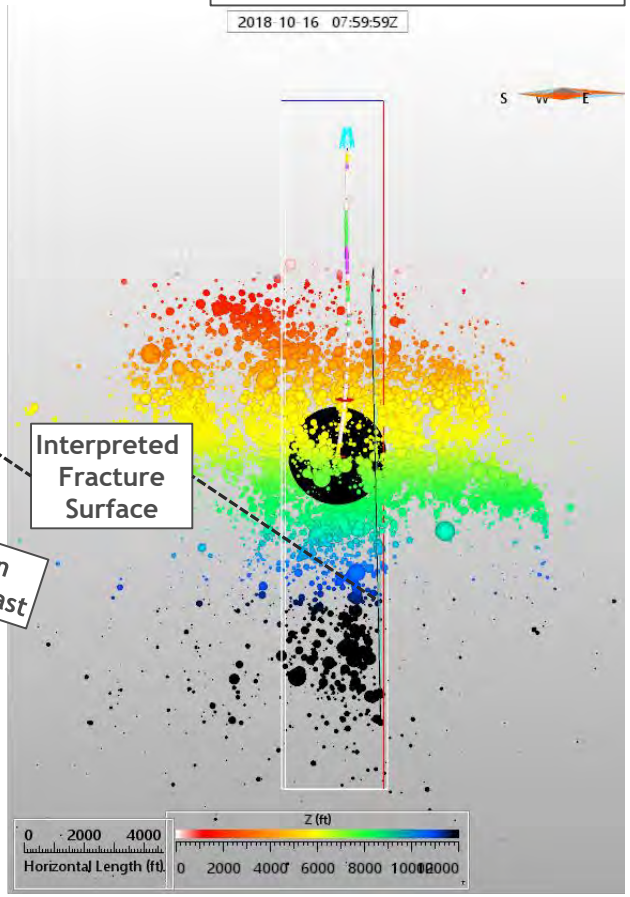
Detailed analysis of a limited subvolume of data can assist in understanding the relationship between water injection, induced seismicity and the 3D structural model.



Map View



View From East-Southeast



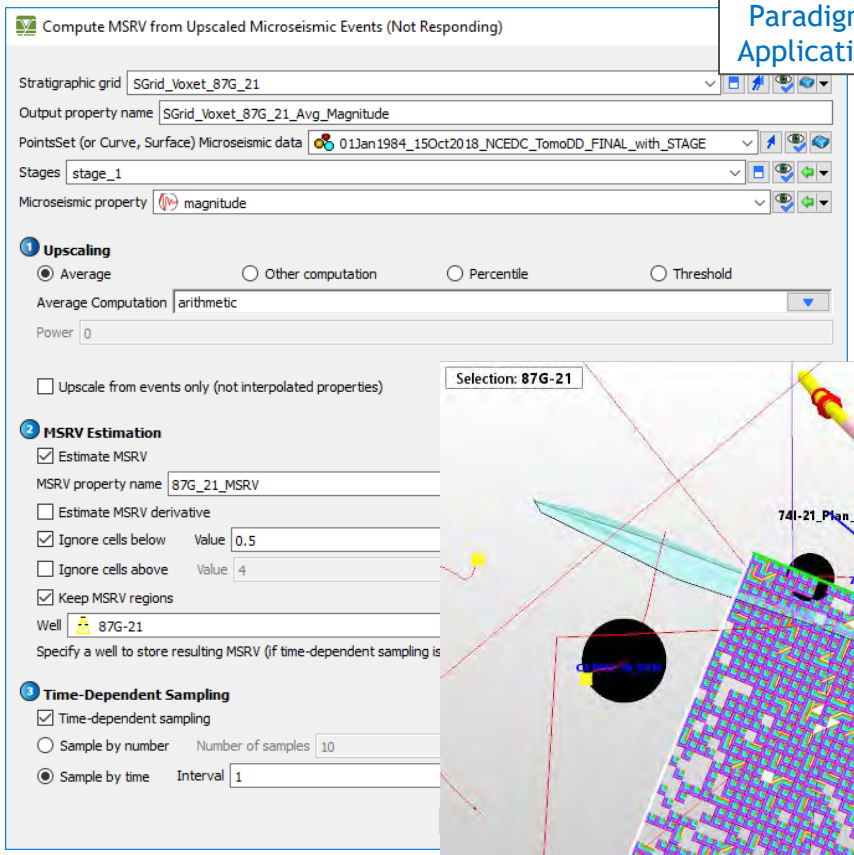
Interpreted Fracture Surface

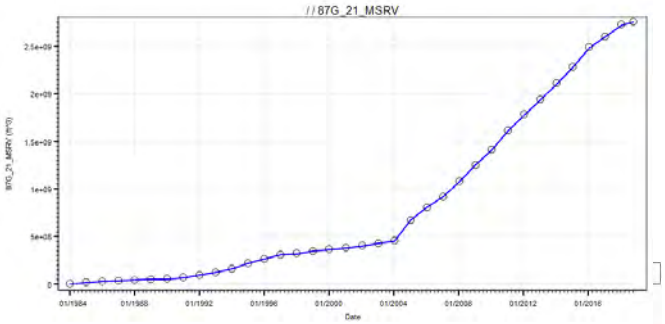
View From East-Southeast

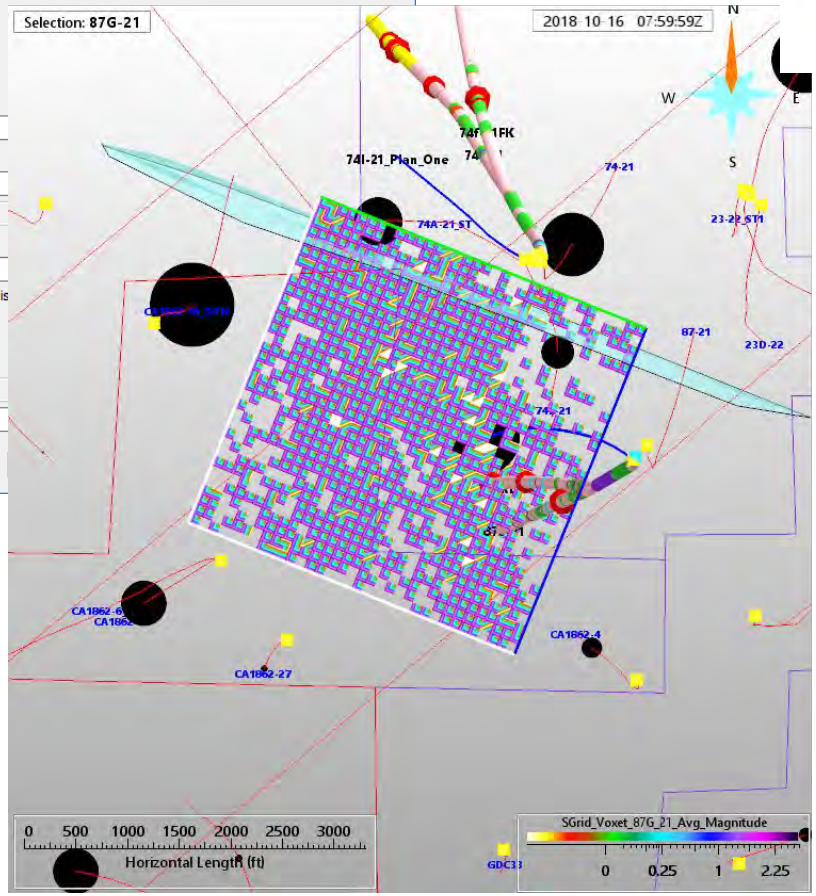
Seismic Monitoring Advisory Committee Meeting

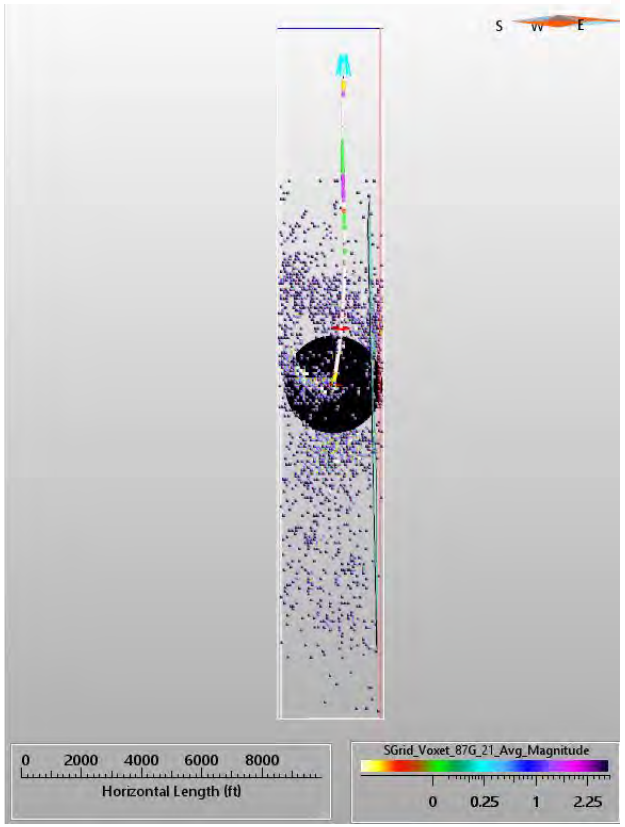
Calistoga Area Microseismic Stimulated Reservoir Volume Analysis

Paradigm Geophysical SKUA GOCAD Software, Originally Developed for Oil and Gas Applications Includes Many Tools For Improved Understanding of Induced Seismicity.

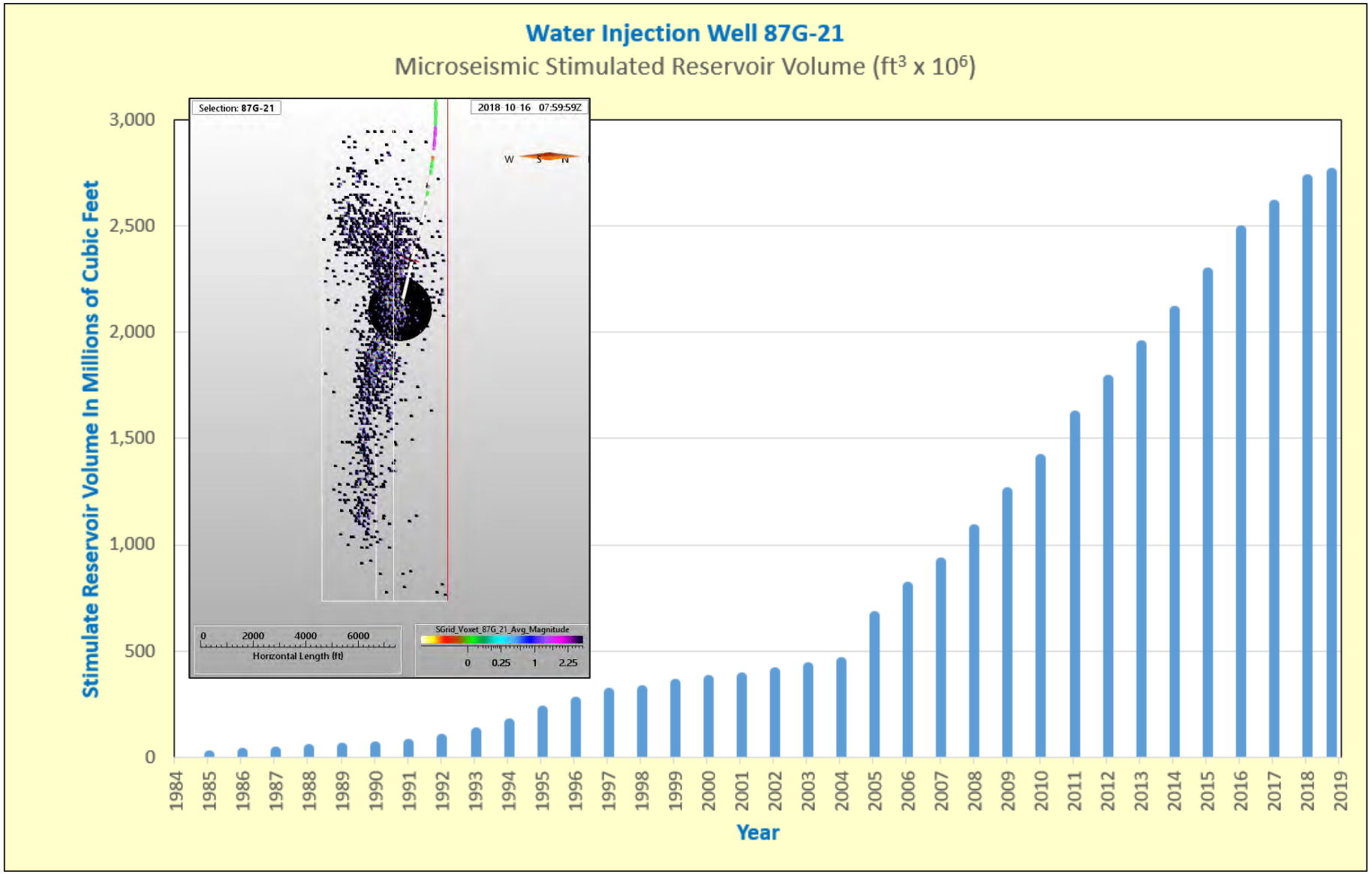






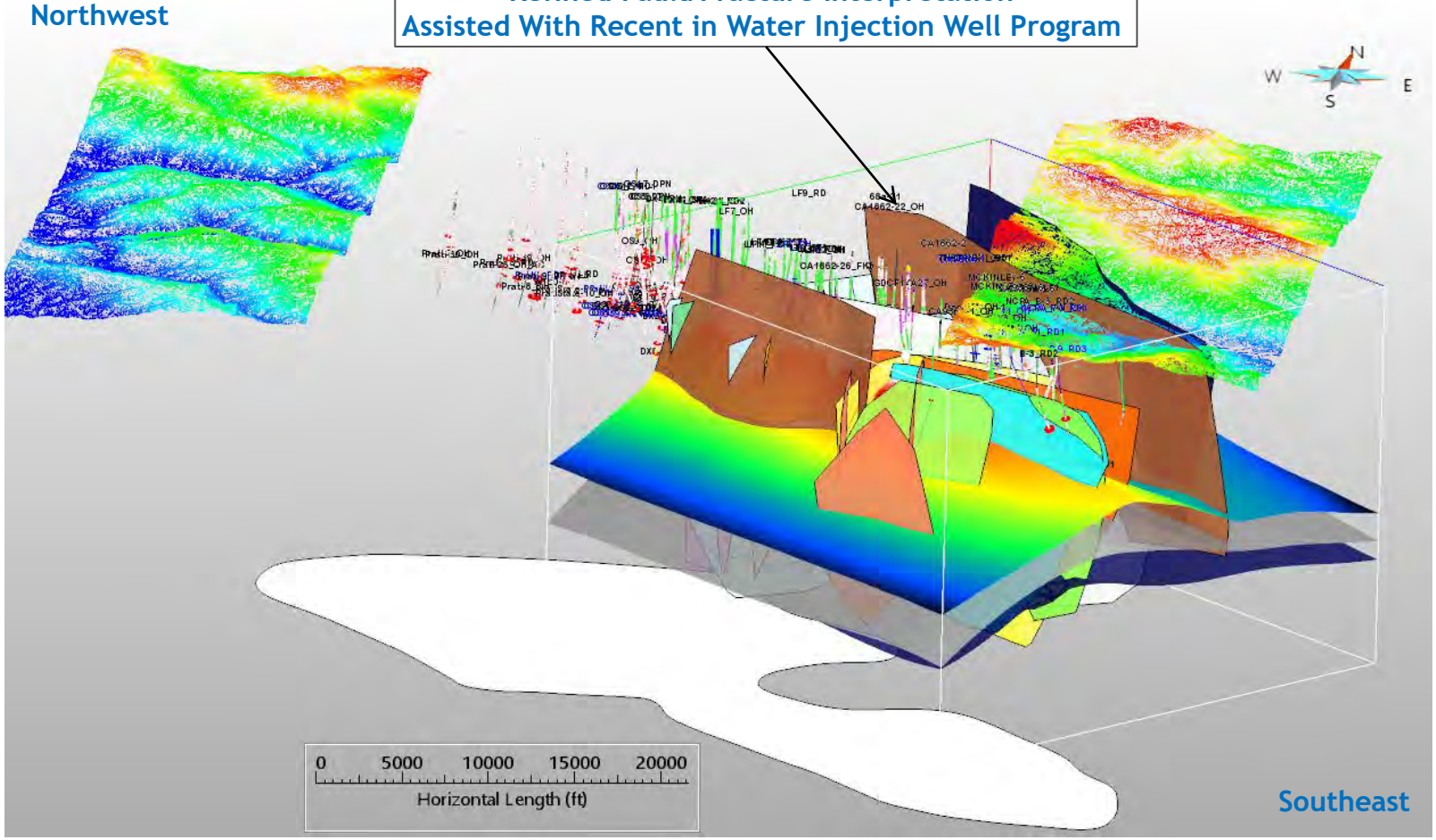


Calistoga Area Microseismic Stimulated Reservoir Volume Analysis



Seismic Monitoring Advisory Committee Meeting
Southeast Geysers Structural Model Development

Calistoga Power Plant Area
Refined Fault/Fracture Interpretation
Assisted With Recent in Water Injection Well Program



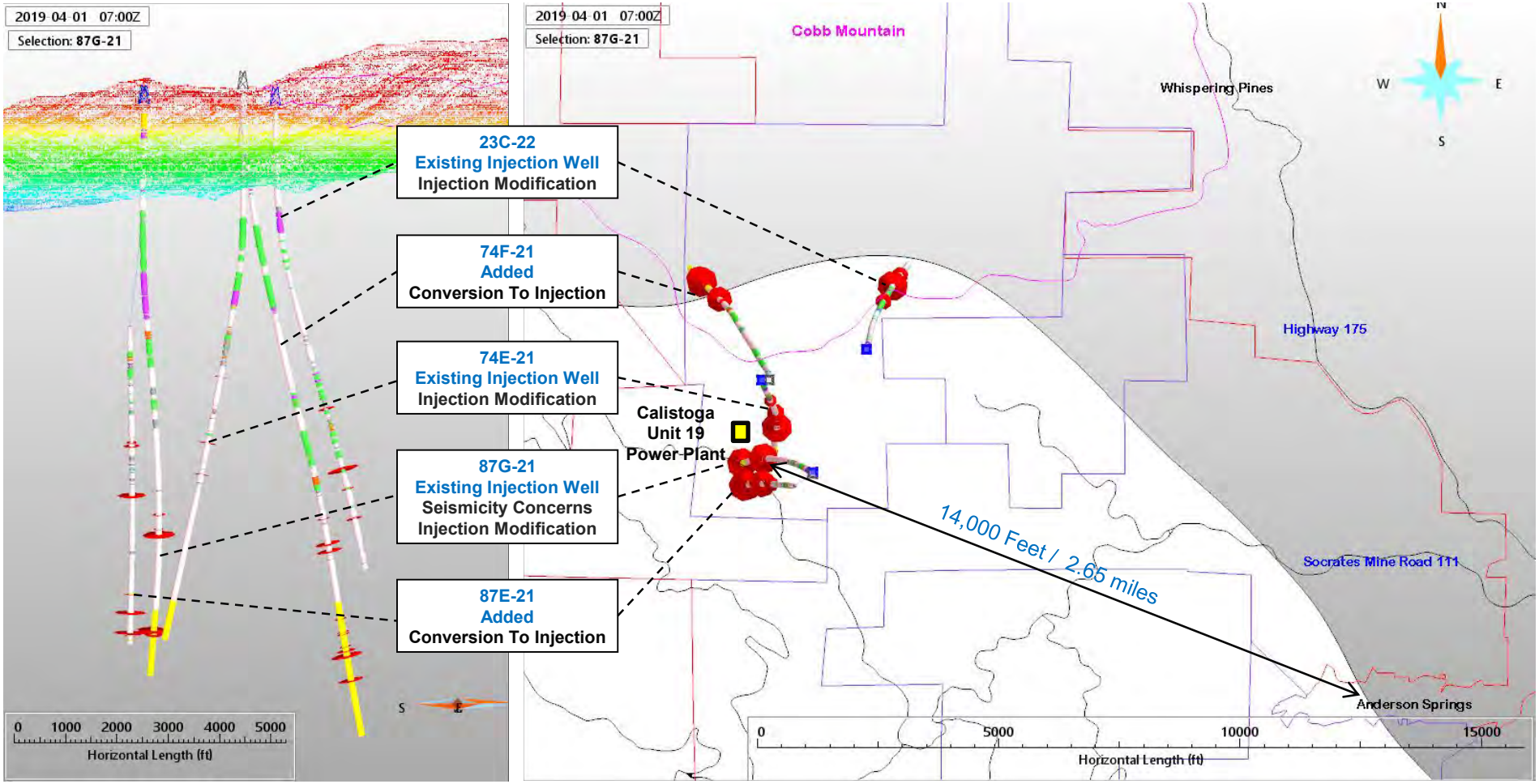
3D Structural Model Building: Oblique 3D view from south-southeast showing the developing 3D structural model within the south half of The Geysers. Shown are color-scaled topographic surfaces "above" the model, the test volume or voxet boundary box, the intersecting faults and 3D structural horizons developed within the 3D structural and stratigraphic workflow, a NW-SE oriented corridor of wells with lithology (rock type) logs assigned, and a deeper surface representing the productive steam reservoir outline.

Seismic Monitoring Advisory Committee Meeting

Better Water Distribution for Seismicity Mitigation

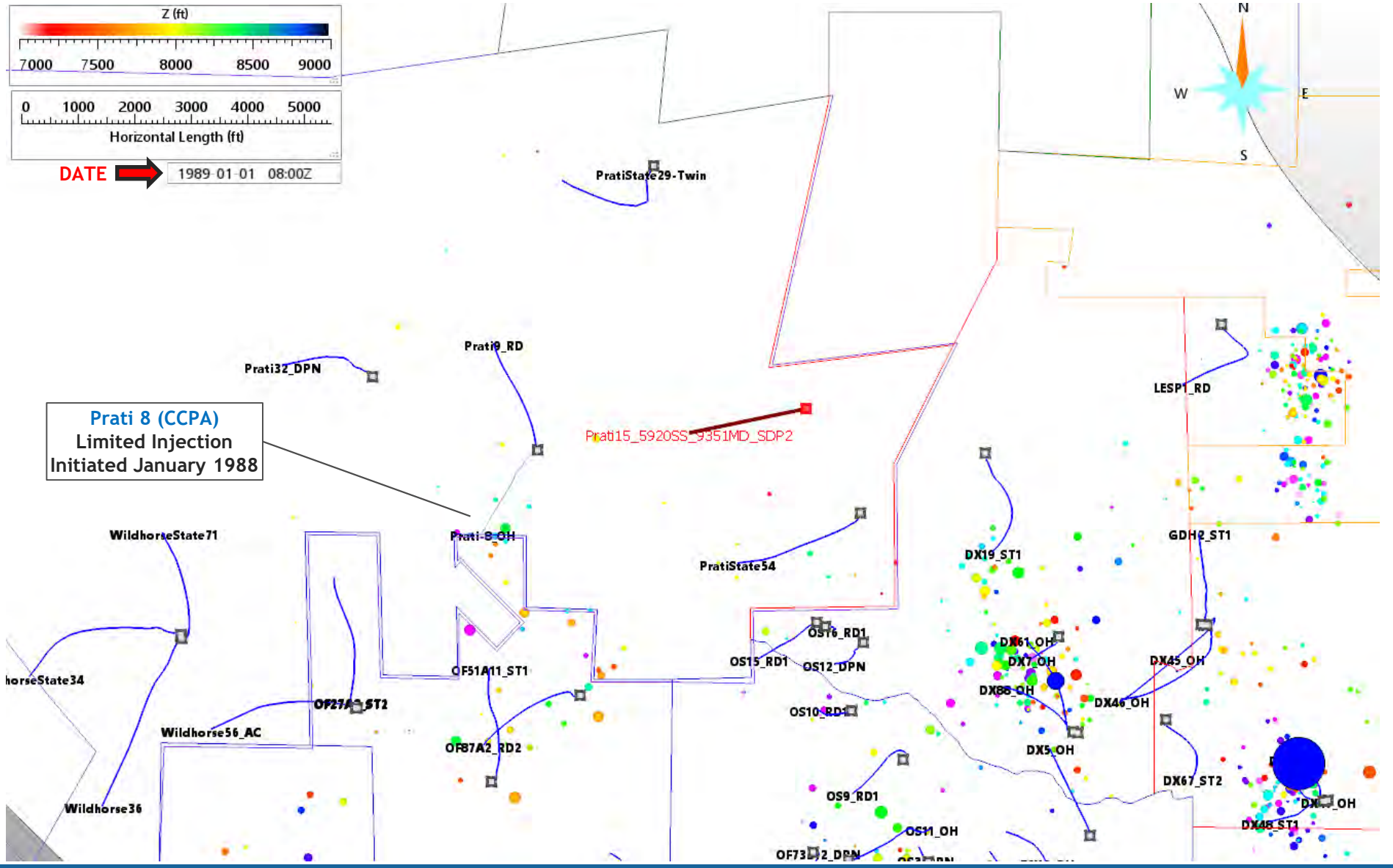
Calistoga Power Plant Area 87G-21

- 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



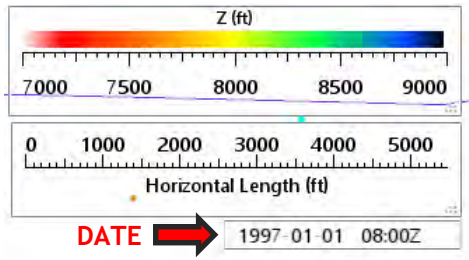
Seismic Monitoring Advisory Committee
Prati 15 Steam Production Well Planning

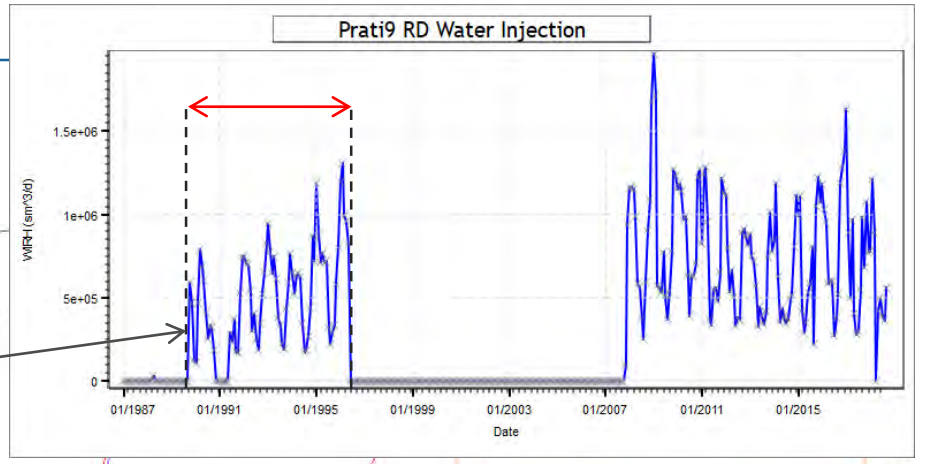
Time Snapshots	1984, 1989, 1997, 2000 through 2018
Seismicity Depth Range	7000' to 9000' Subsea



Seismic Monitoring Advisory Committee
Prati 15 Steam Production Well Planning

Time Snapshots	1984, 1989, 1997, 2000 through 2018
Seismicity Depth Range	7000' to 9000' Subsea





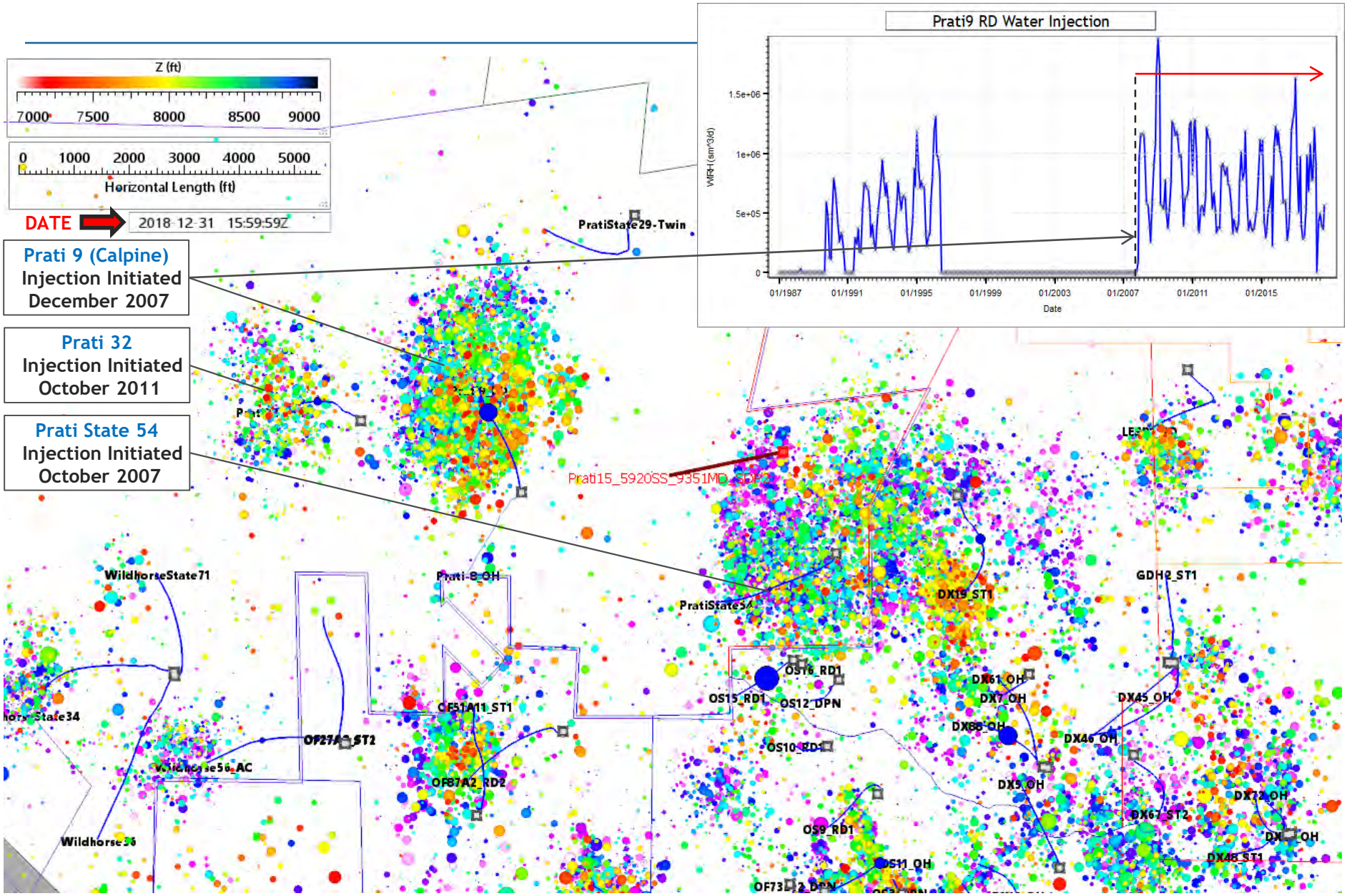
Prati 9 (CCPA)
Early Injection Period
November 1989
May 1996

Prati 8 (CCPA)
Limited Injection
Initiated January 1988

Seismic Monitoring Advisory Committee

Prati 15 Steam Production Well Planning

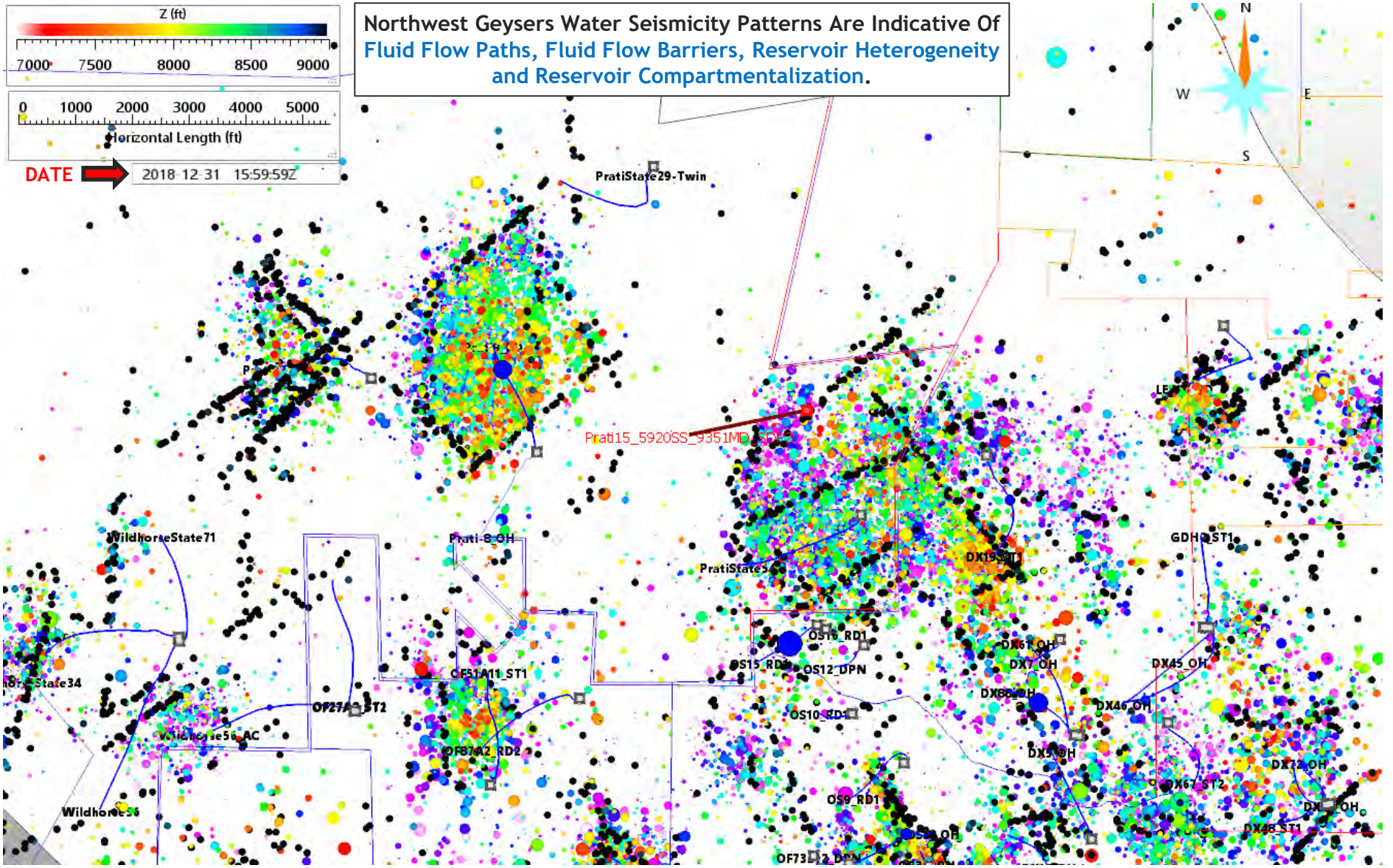
Time Snapshots	1984, 1989, 1997, 2000 through 2018
Seismicity Depth Range	7000' to 9000' Subsea



Seismic Monitoring Advisory Committee

Prati 15 Steam Production Well Planning

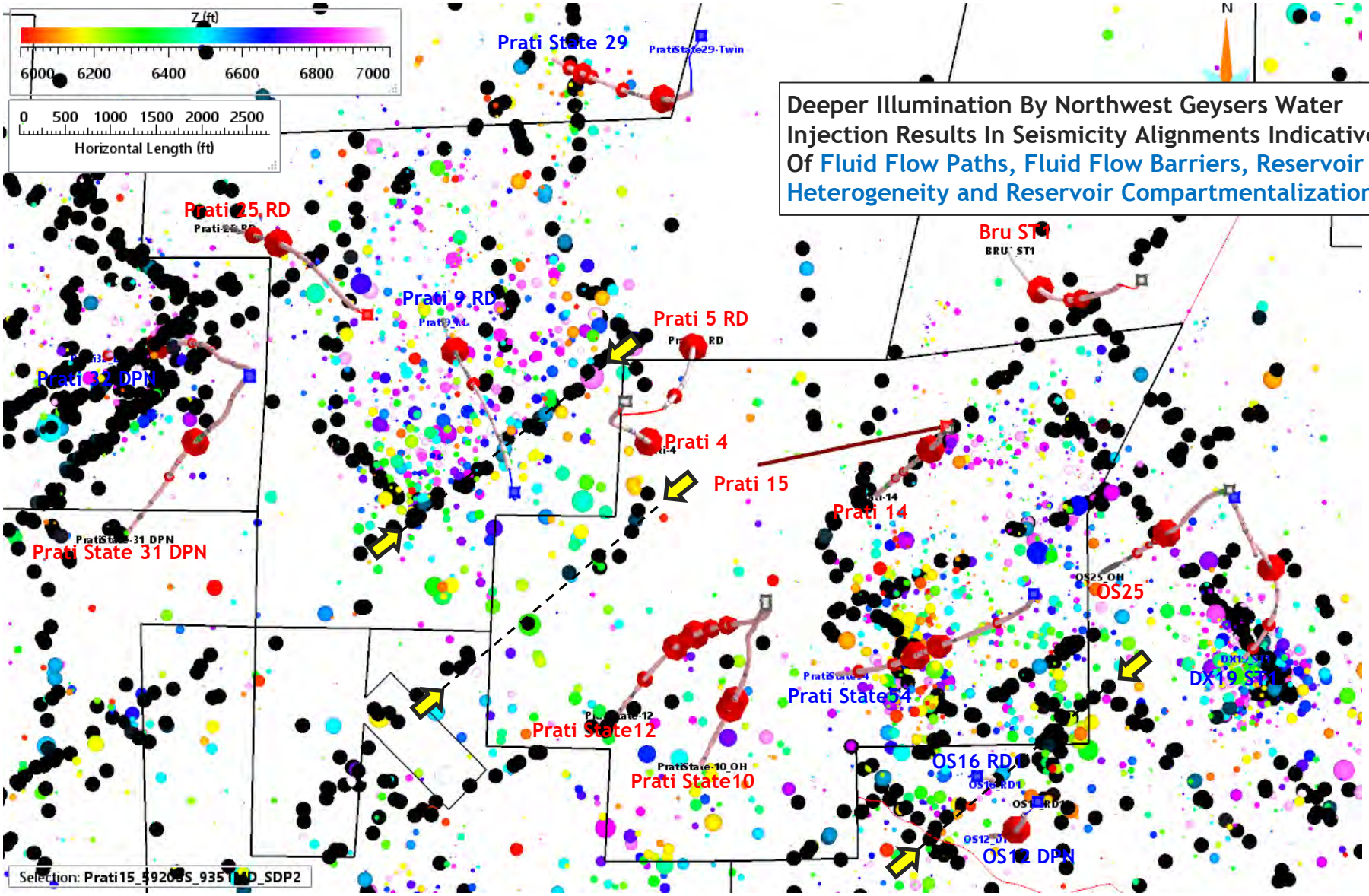
Time Snapshots	1984, 1989, 1997, 2000 through 2018
Seismicity Depth Range	7000' to 9000' Subsea
Fault Pick Depth Range	7000' to 9000' Subsea



Seismic Monitoring Advisory Committee

Prati 15 Steam Production Well Planning
Seismicity Slice #1

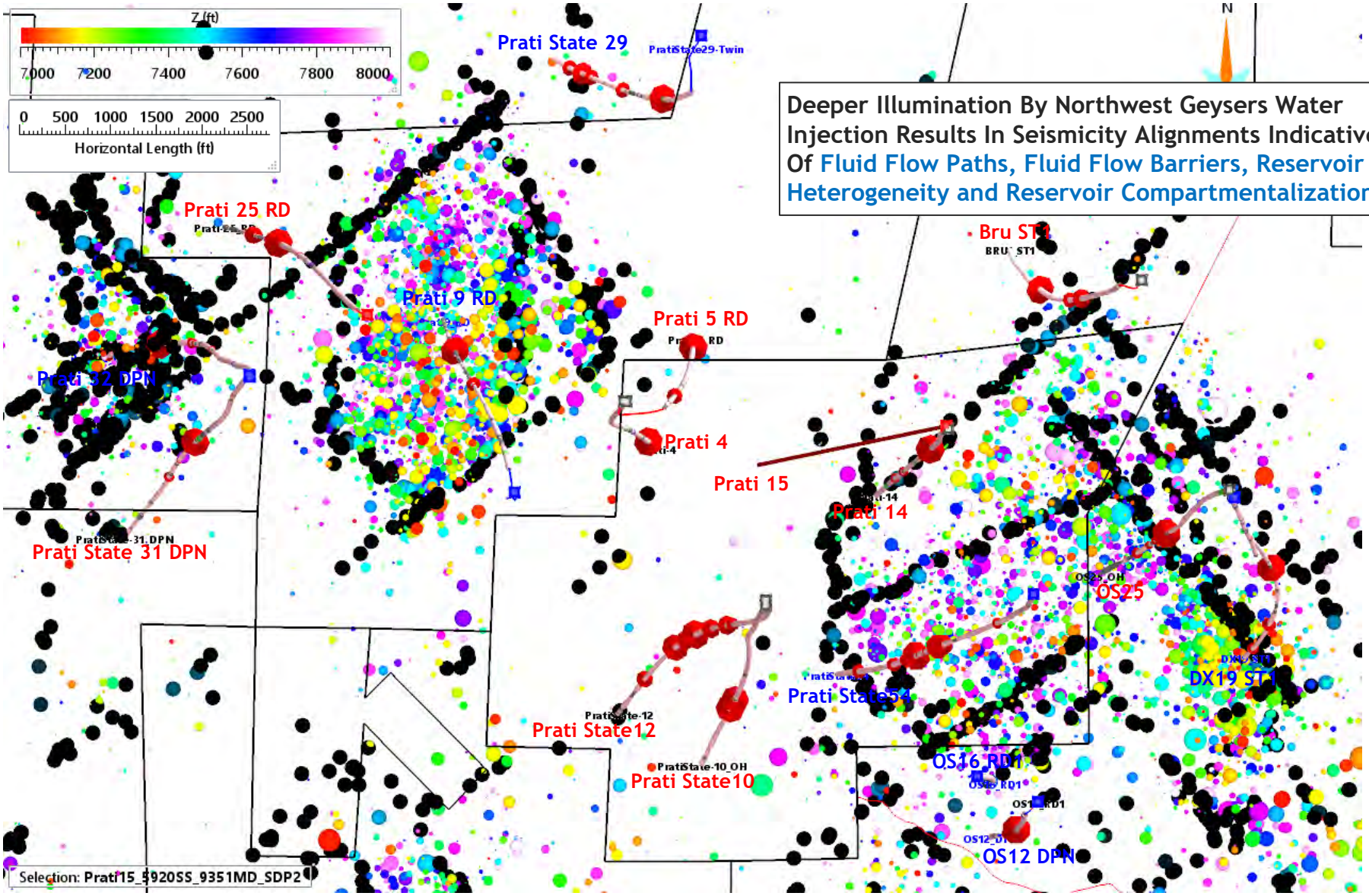
Seismicity Time Range	1984 through 2018
Seismicity Depth Range	6000’ to 7000’ Below Sea Level
Fault Pick Depth Range	5500’ to 7500’ Below Sea Level



Seismic Monitoring Advisory Committee

Prati 15 Steam Production Well Planning
Seismicity Slice #2

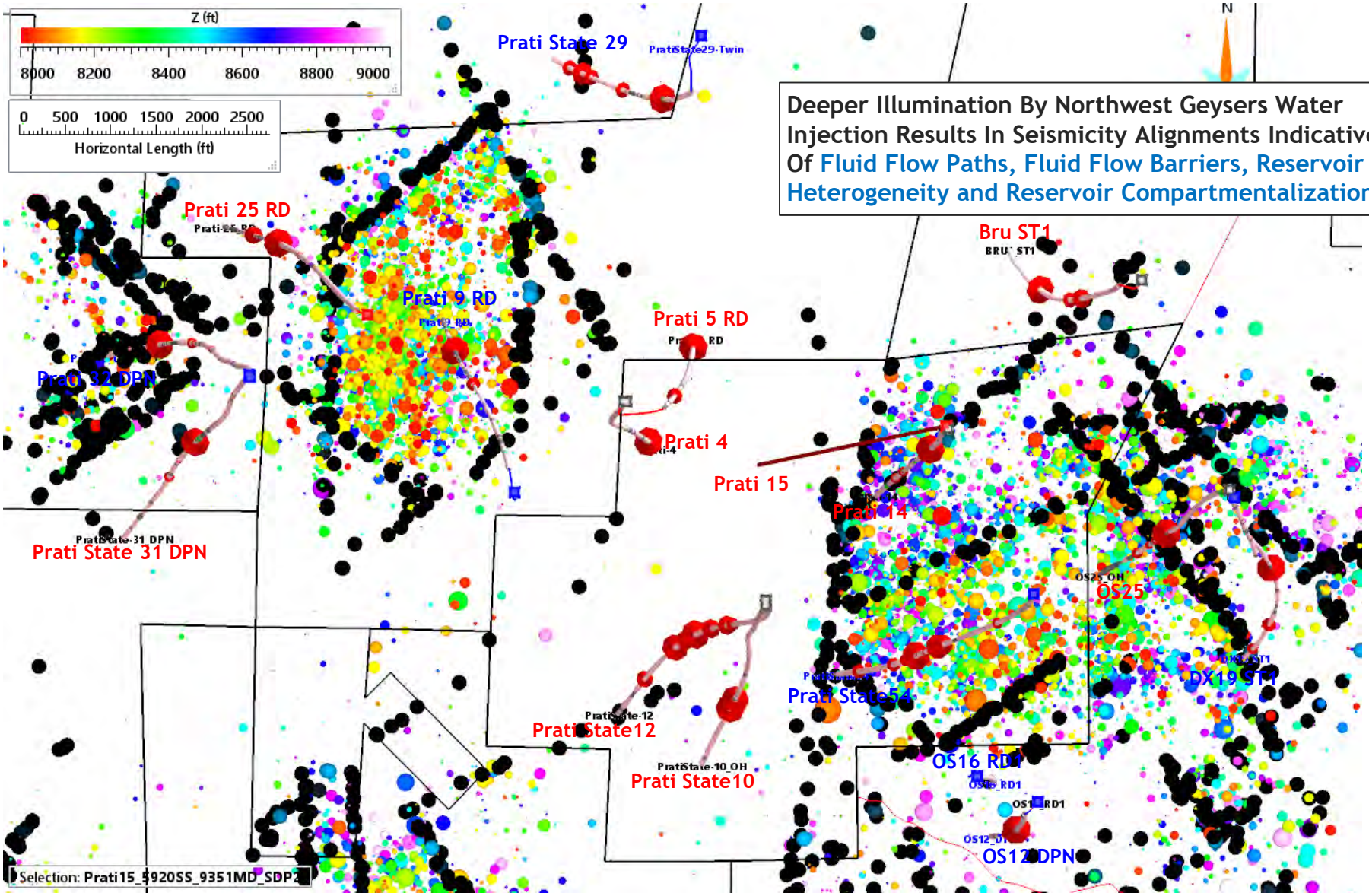
Seismicity Time Range	1984 through 2018
Seismicity Depth Range	7000’ to 8000’ Below Sea Level
Fault Pick Depth Range	6500’ to 8500’ Below Sea Level



Seismic Monitoring Advisory Committee

Prati 15 Steam Production Well Planning Seismicity Slice #3

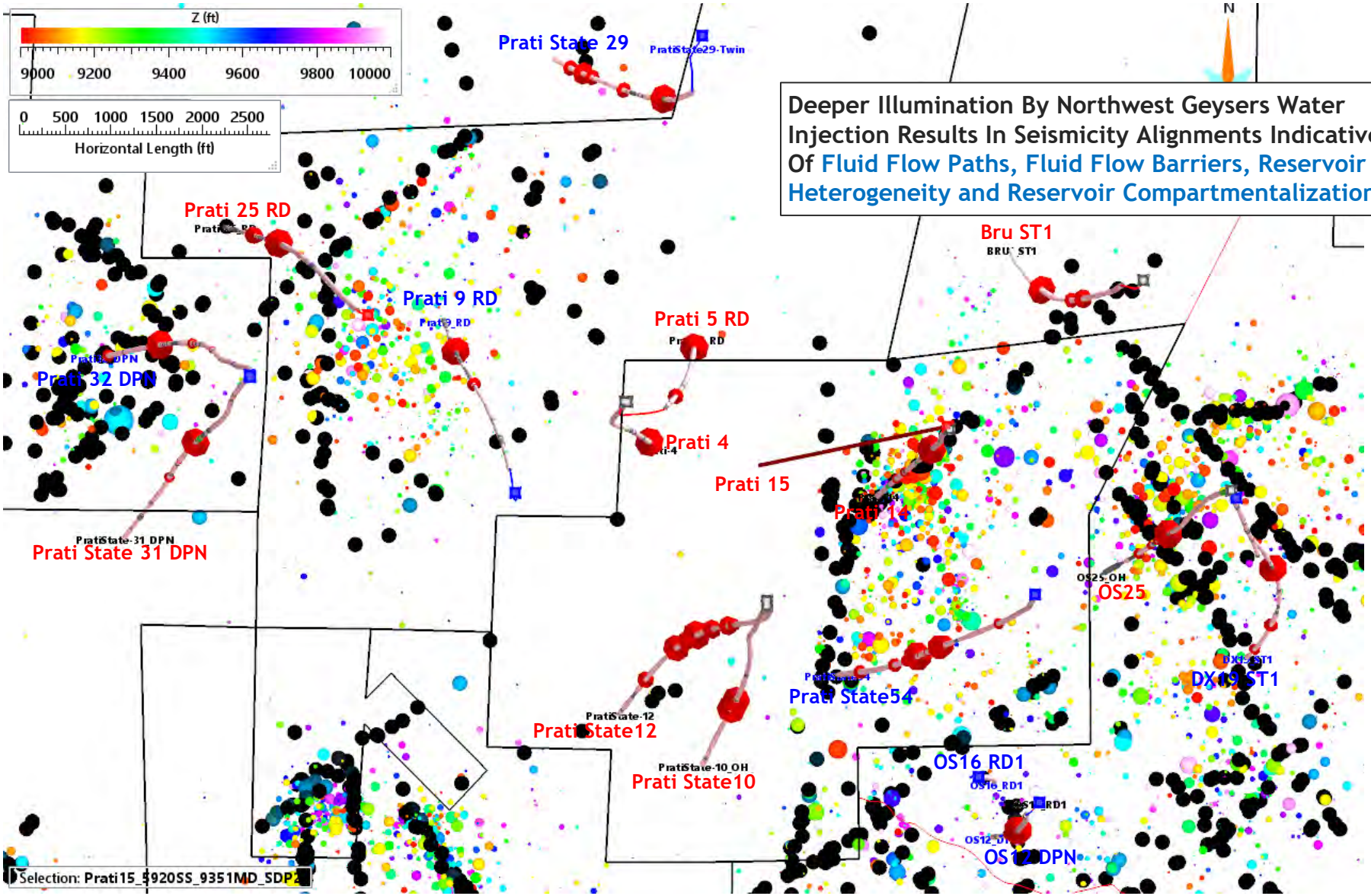
Seismicity Time Range	1984 through 2018
Seismicity Depth Range	8000’ to 9000’ Below Sea Level
Fault Pick Depth Range	7500’ to 9500’ Below Sea Level



Seismic Monitoring Advisory Committee

Prati 15 Steam Production Well Planning
Seismicity Slice #4

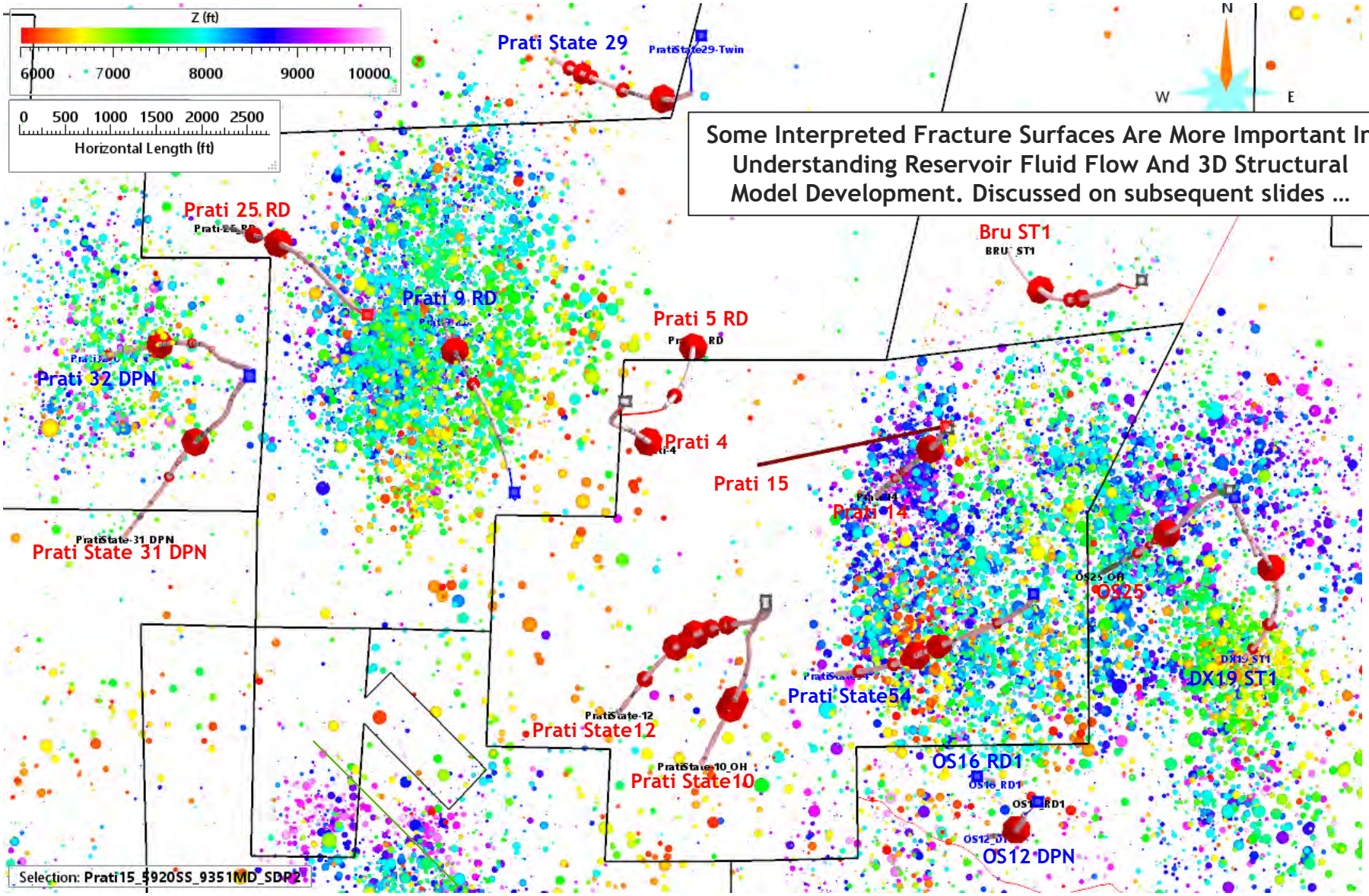
Seismicity Time Range	1984 through 2018
Seismicity Depth Range	9000' to 10000' Below Sea Level
Fault Pick Depth Range	8500' to 10500' Below Sea Level



Seismic Monitoring Advisory Committee

Prati 15 Steam Production Well Planning
Active Wells in Vicinity

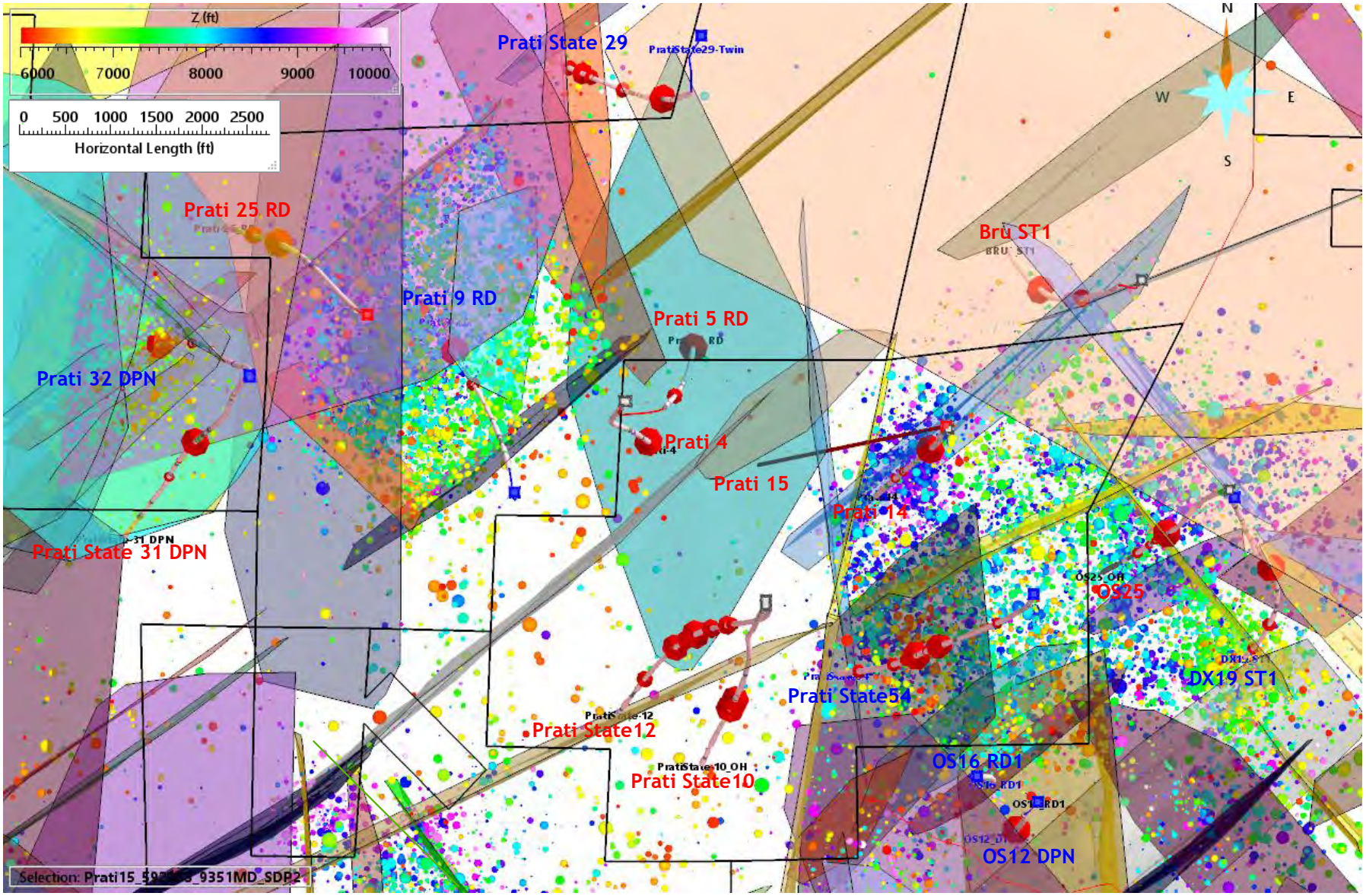
Seismicity Time Range	1984 through 2018
Seismicity Depth Range	6000' to 10000' Below Sea Level



Seismic Monitoring Advisory Committee

Prati 15 Steam Production Well Planning
All Interpreted Fracture Surfaces

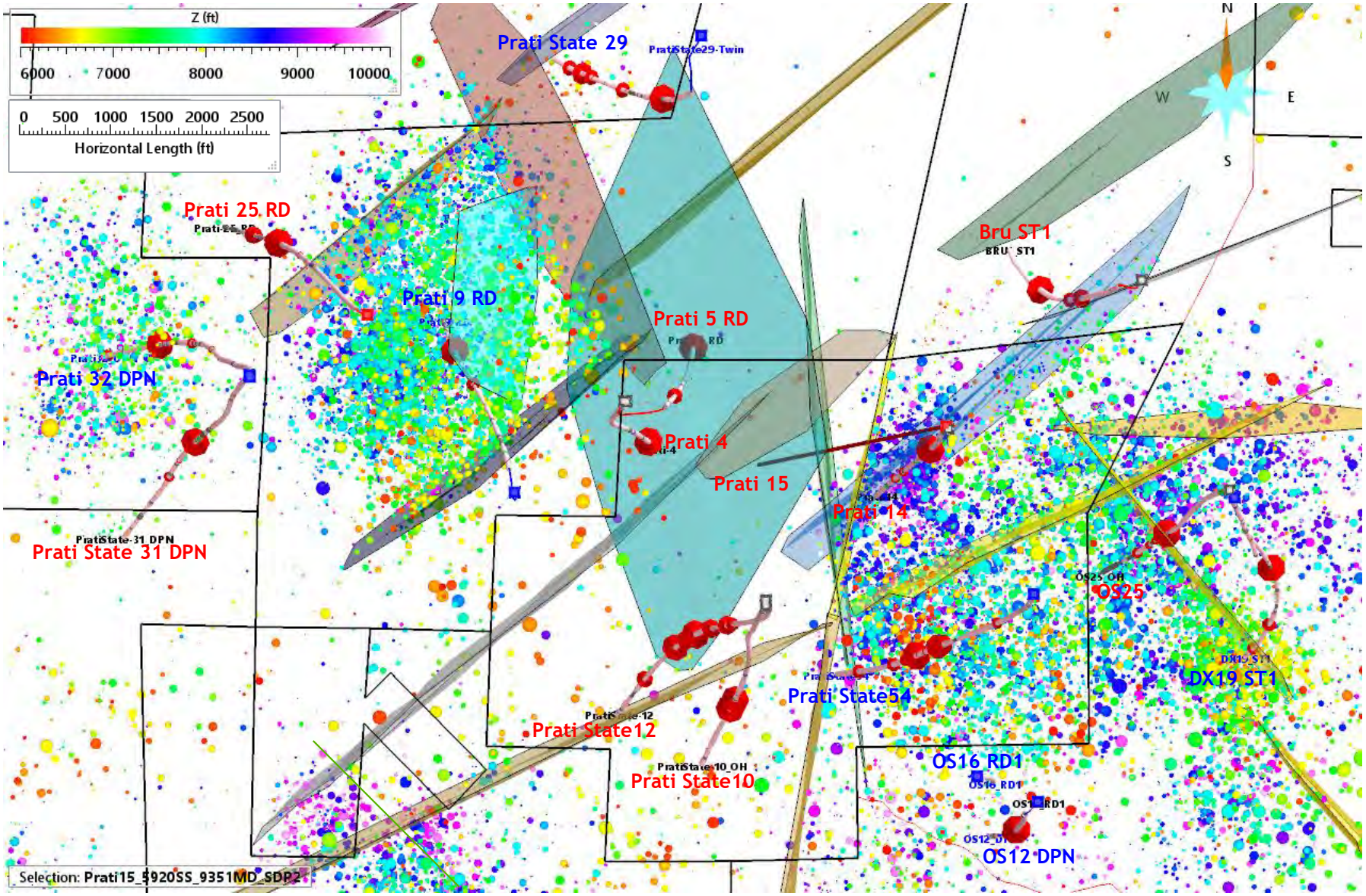
Seismicity Time Range	1984 through 2018
Seismicity Depth Range	6000' to 9000' Below Sea Level



Seismic Monitoring Advisory Committee

Prati 15 Steam Production Well Planning
Limited Interpreted Fracture Surfaces

Seismicity Time Range	1984 through 2018
Seismicity Depth Range	6000' to 9000' Below Sea Level



Seismic Monitoring Advisory Committee

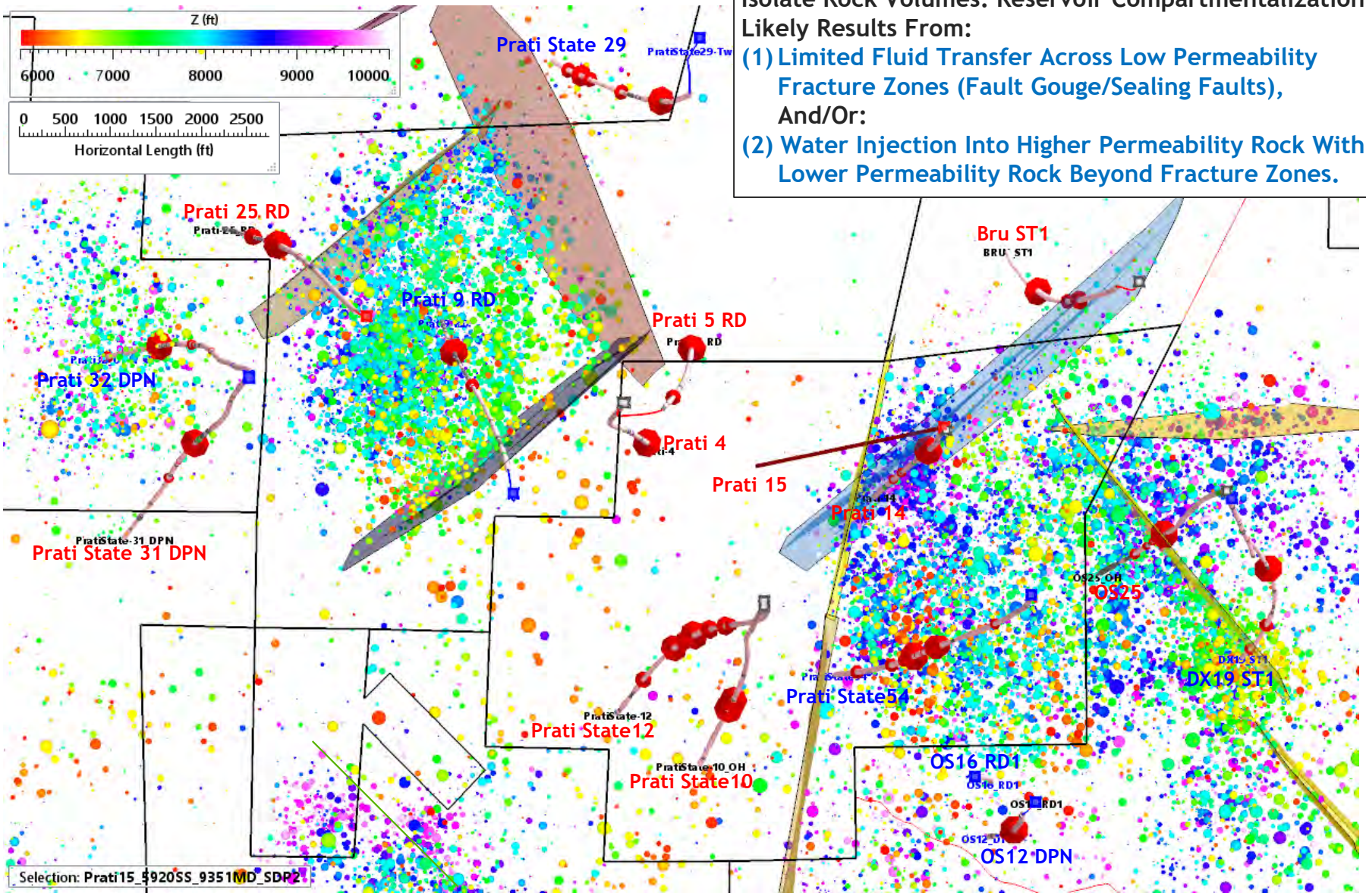
Prati 15 Steam Production Well Planning
Very Limited Interpreted Fracture Surfaces

Seismicity Time Range	1984 through 2018
Seismicity Depth Range	6000' to 9000' Below Sea Level

The Selected Fracture Surfaces Seem To Significantly Isolate Rock Volumes. Reservoir Compartmentalization Likely Results From:

(1) Limited Fluid Transfer Across Low Permeability Fracture Zones (Fault Gouge/Sealing Faults), And/Or:

(2) Water Injection Into Higher Permeability Rock With Lower Permeability Rock Beyond Fracture Zones.

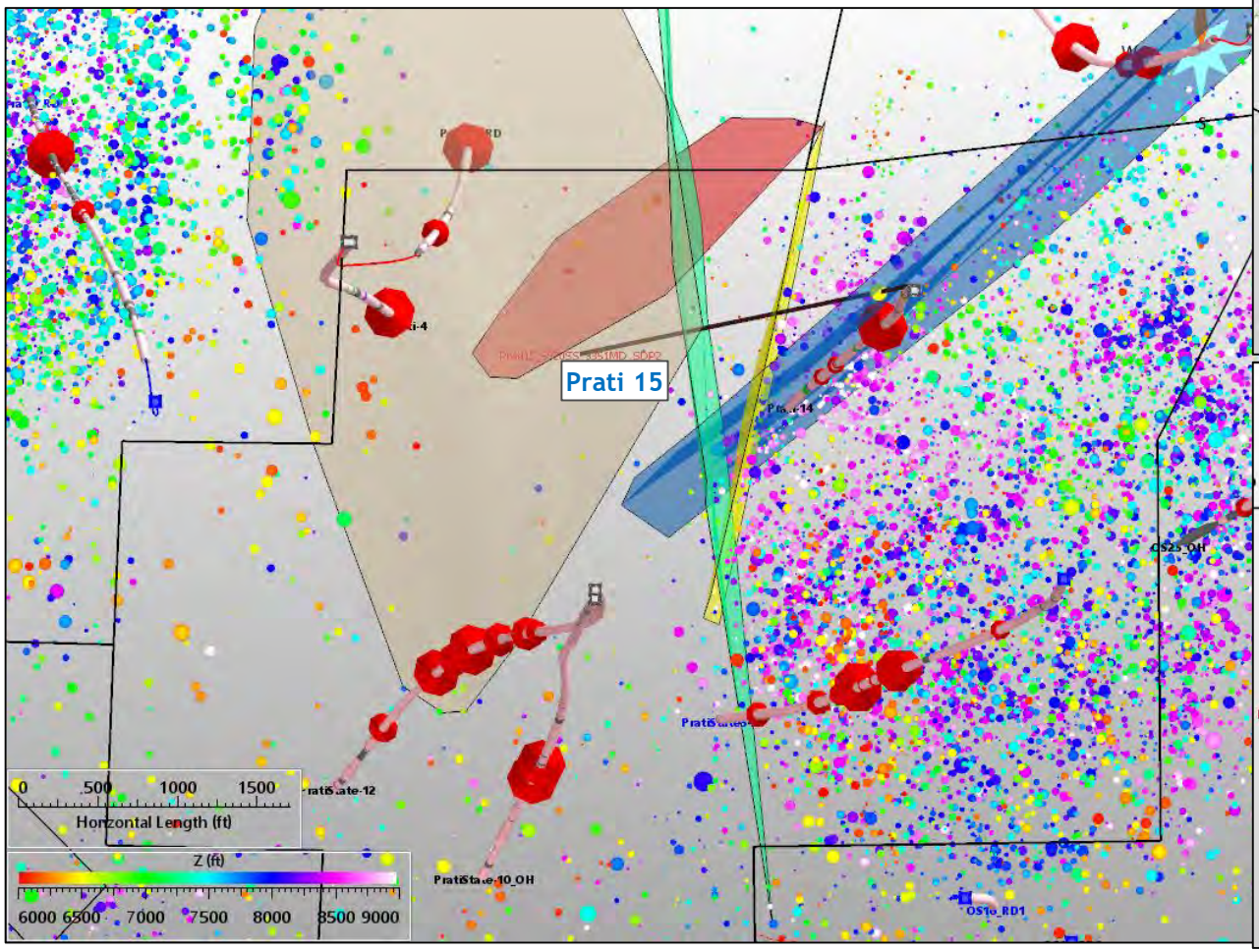


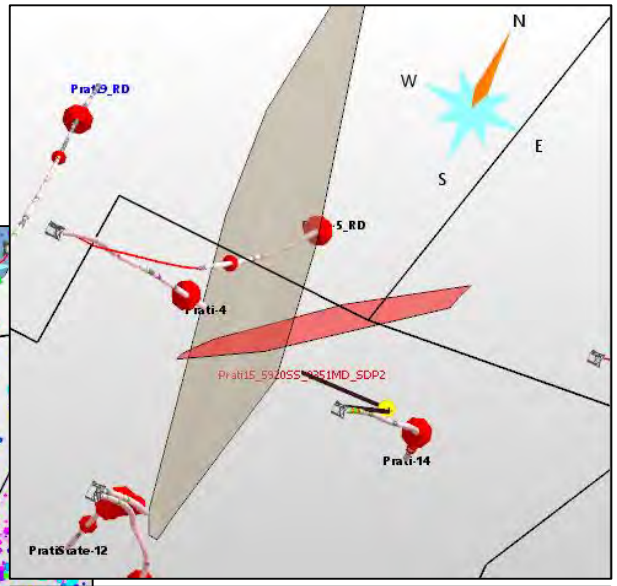
Seismic Monitoring Advisory Committee

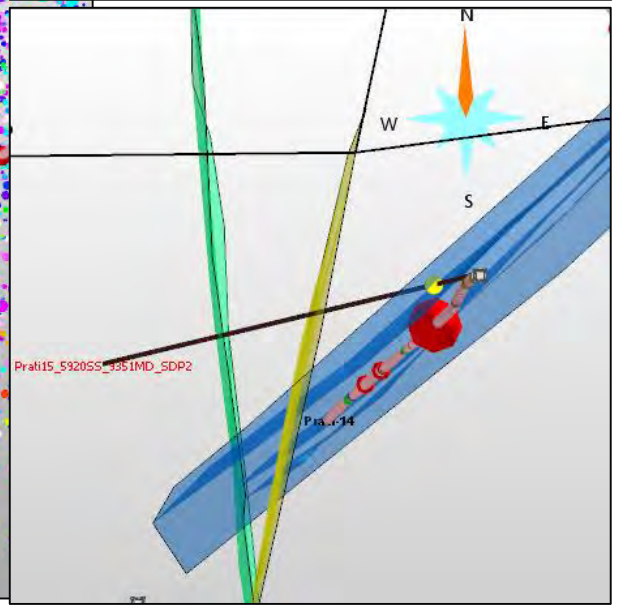
Prati 15 Steam Production Well Planning
Trajectory and Interpreted Fracture Surfaces

Seismicity Time Range	1984 through 2018
Seismicity Depth Range	6000’ to 9000’ Below Sea Level

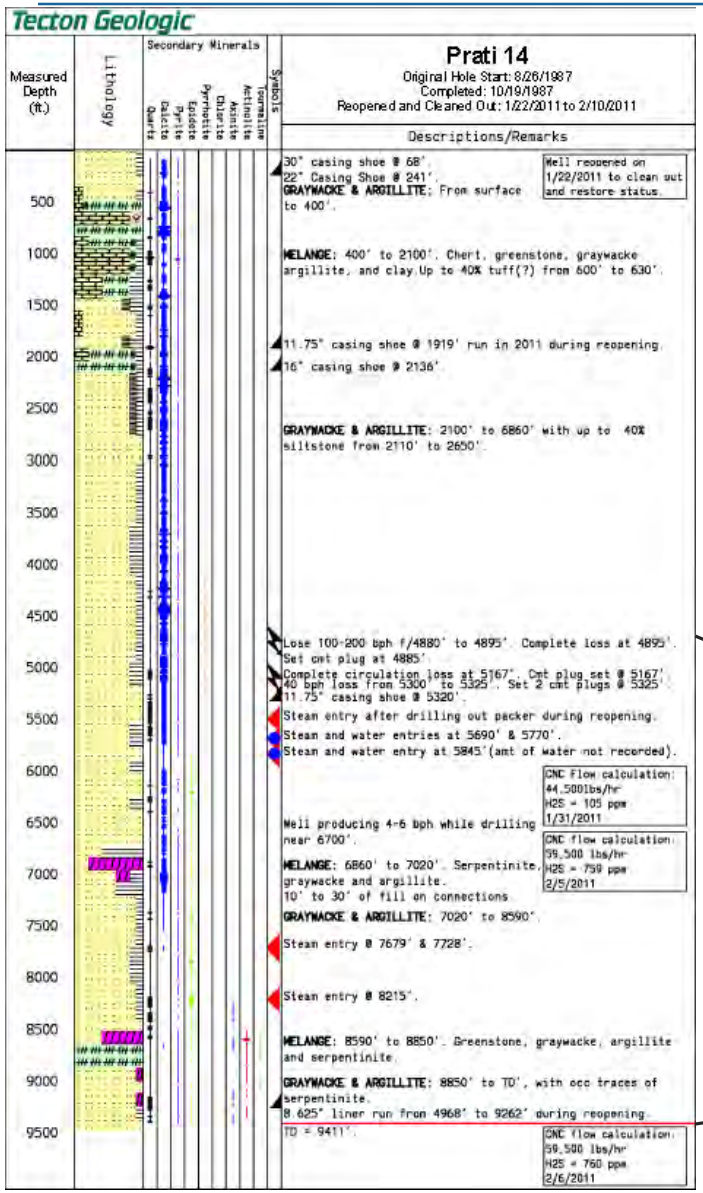
- **3770’ MD:** Blue fracture surface intersection.
- **5760’ MD:** Yellow fracture surface intersection.
- **7410’ MD:** Green fracture surface intersection.
- **≥1750’ Separation:** Southeast of northwest dipping red fracture surface.
- **≥1900’ Separation:** Below the west dipping light brown fracture surface.

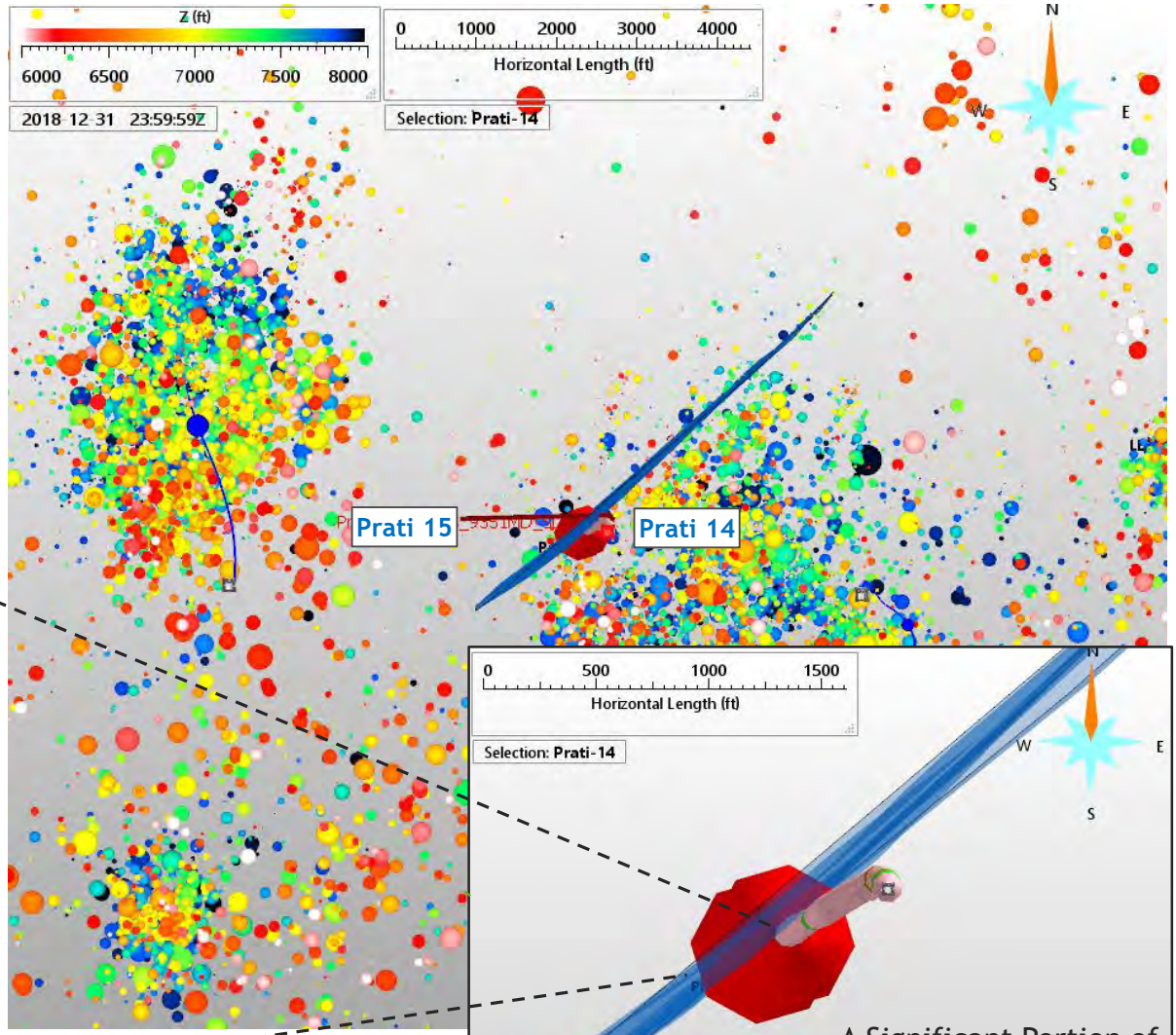






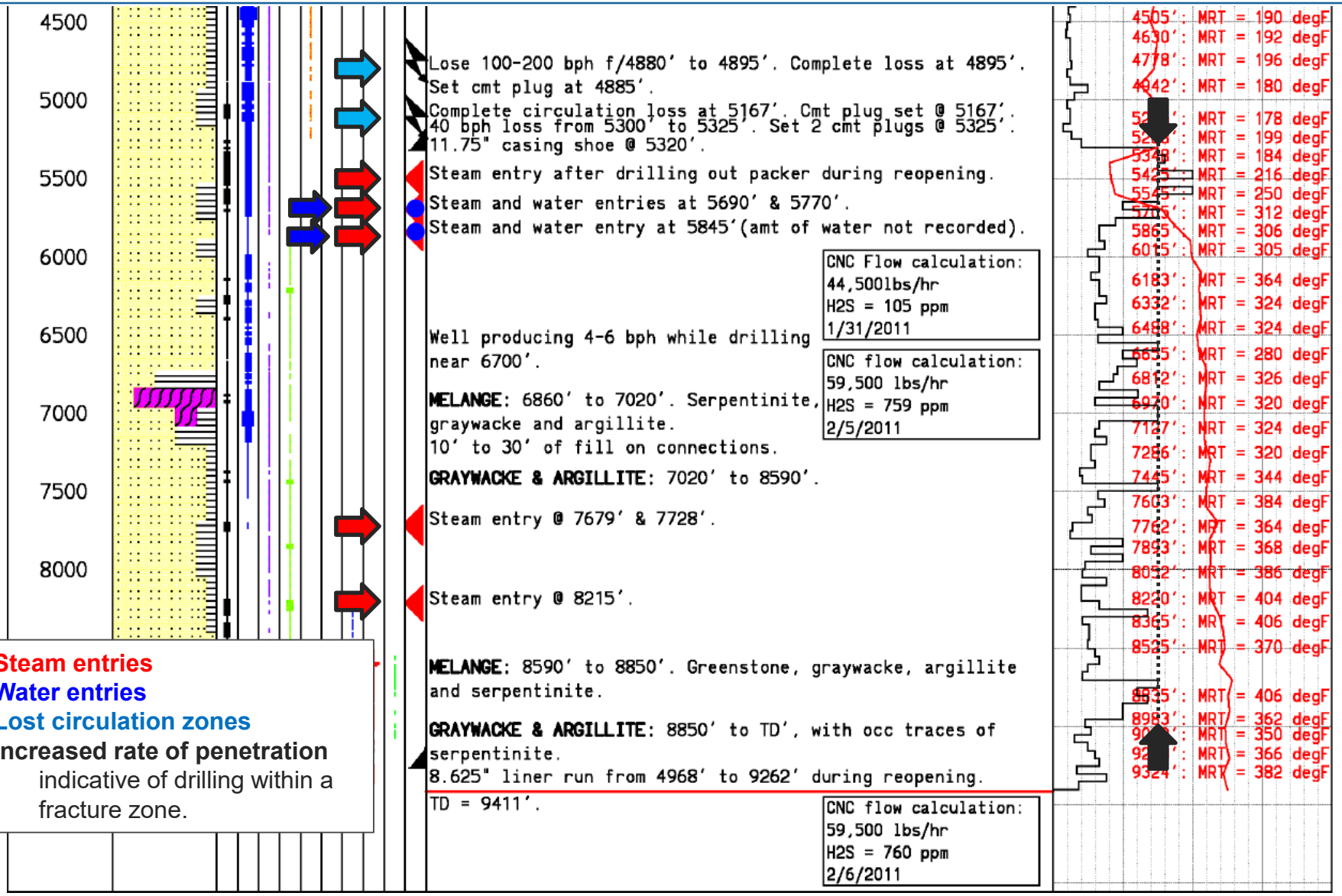
Prati 14 High Permeability Zone Correlates With Fracture Zone Defined By Seismicity Patterns





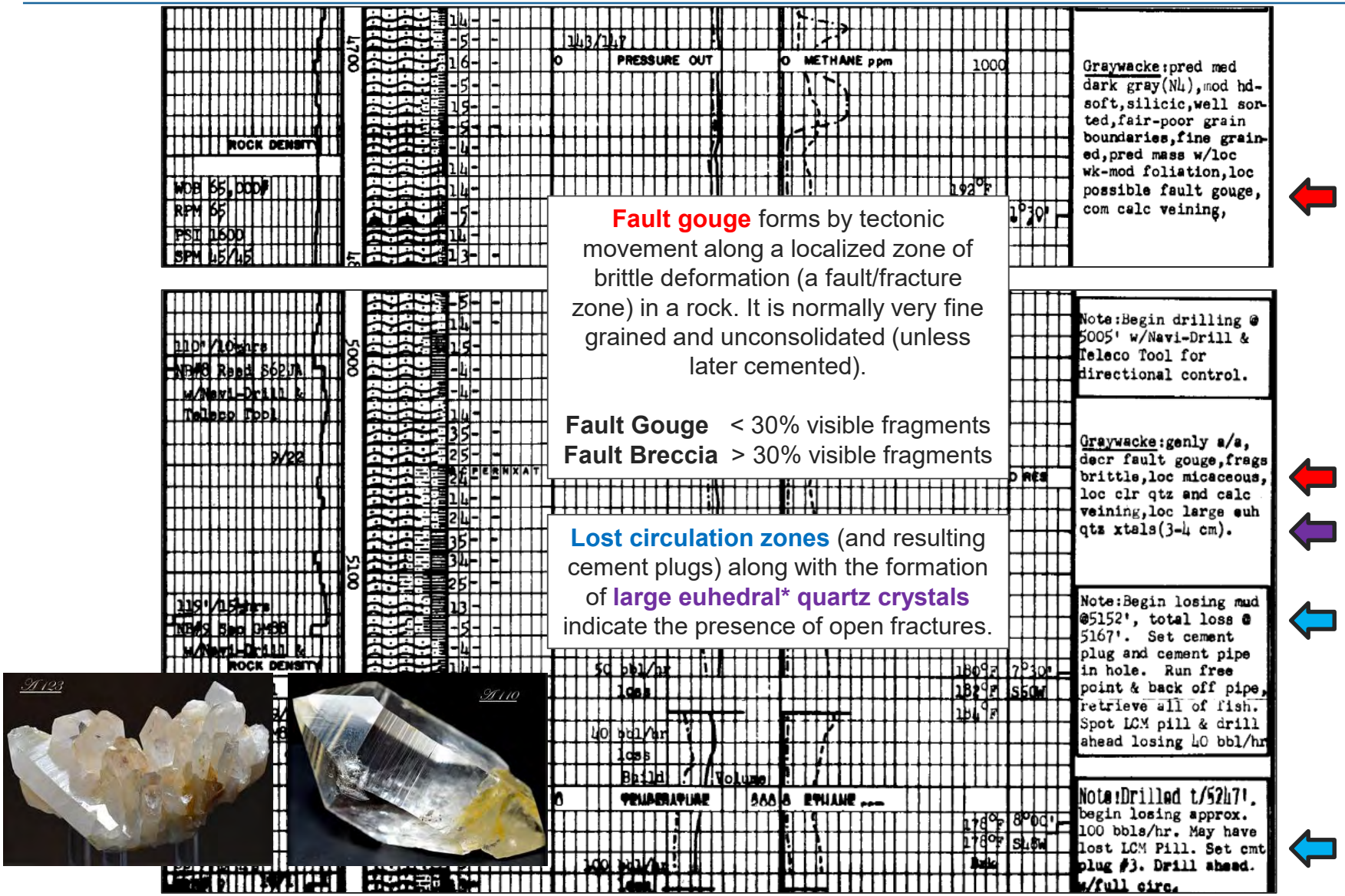
Seismic Monitoring Advisory Committee Meeting

Prati 14 High Permeability Zone Seen On Tecton Geologic Summary Log



- **Steam entries**
- **Water entries**
- **Lost circulation zones**
- **Increased rate of penetration**
  indicative of drilling within a fracture zone.

Prati 14 High Permeability Zone Correlates With Fracture Zone Defined By Lithology Log



*euhedral: Mineral crystal faces correspond to the regular crystal form unconstrained by adjacent minerals.

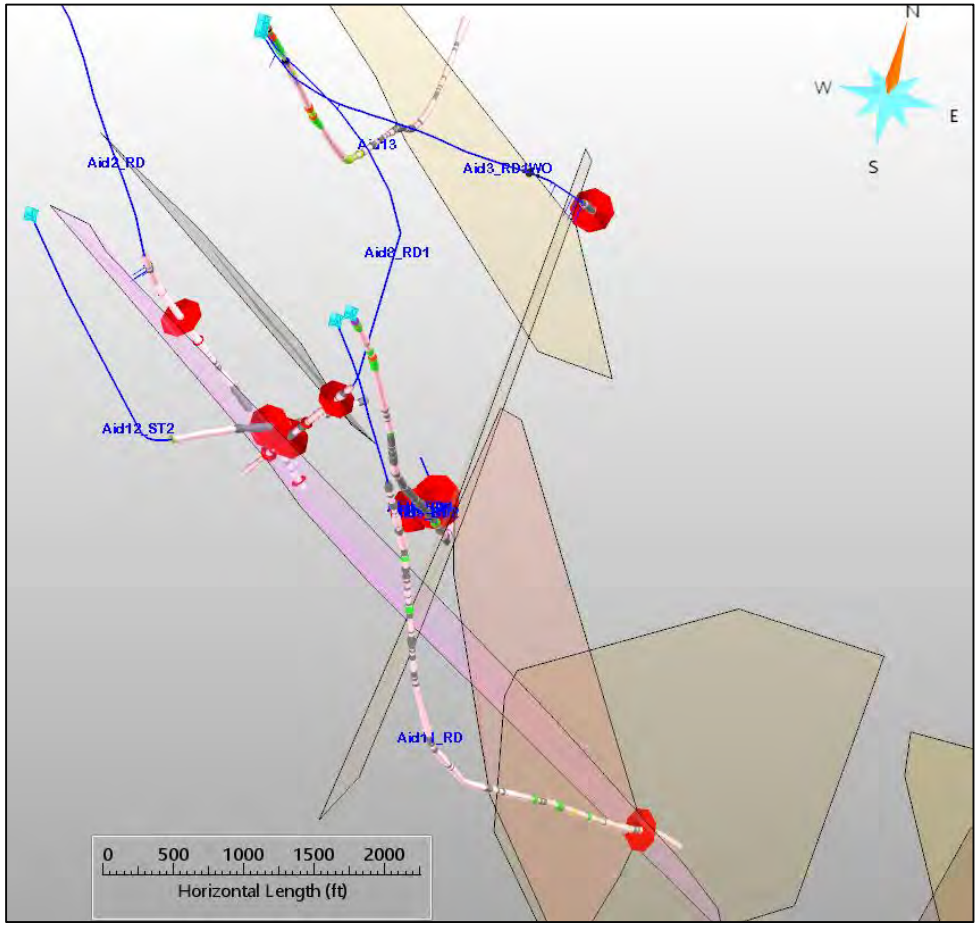
Seismic Monitoring Advisory Committee Meeting

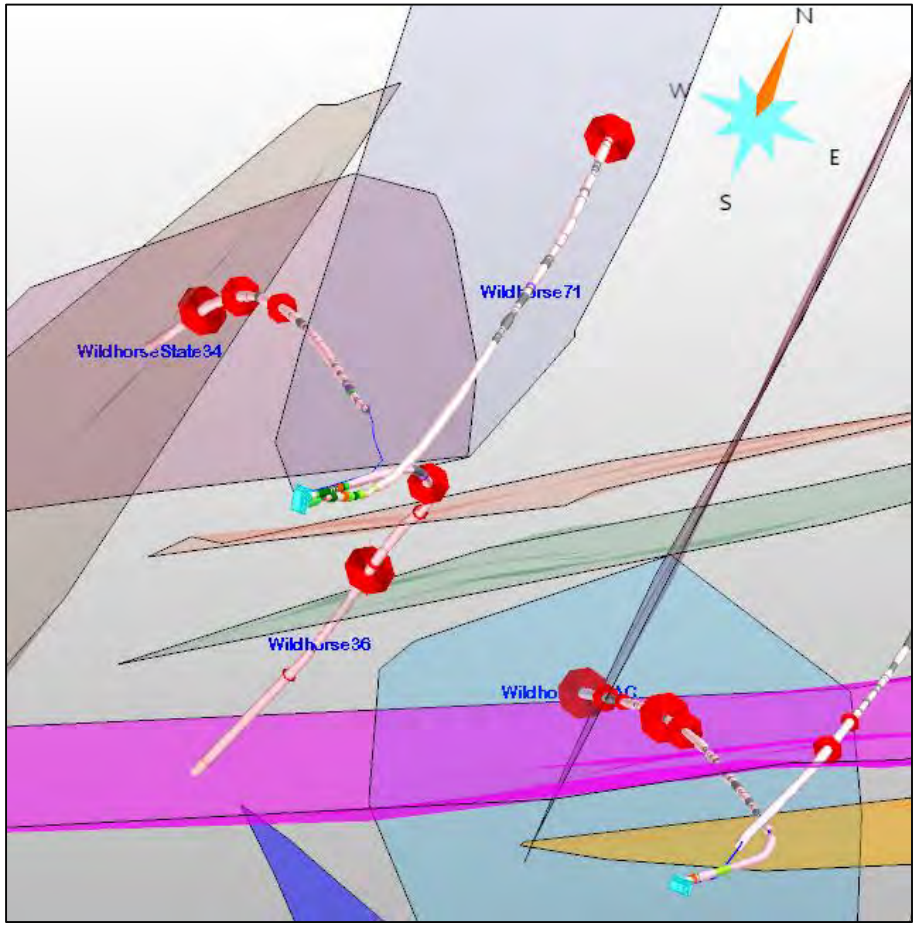
Aidlin and Wildhorse Area 3D Fault Interpretation (Northwest Geysers)
Water injection Well Steam Entries vs. Interpreted Fracture Surfaces (Unbiased*)

Aidlin Area (left) and Wildhorse Area (right)

The majority of significant steam entries for the water injection wells shown occur at *approximately* the intersection with the interpreted fracture surfaces. Fluid flow from water injection wells appear to be illuminating fault/fracture systems.

Many fault/fracture surface associated with steam production wells are not illuminated by seismicity.





*Unbaised = fracture surfaces as seen were initially interpreted using only seismicity alignments

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

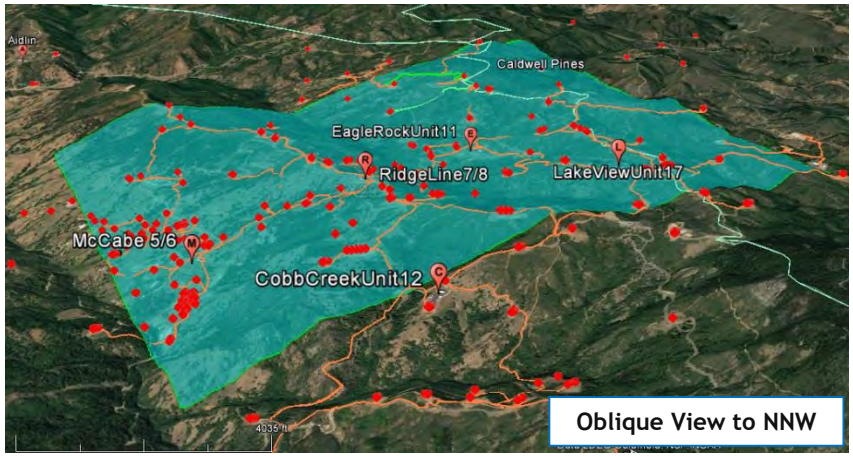
Lawrence Berkeley National Laboratory

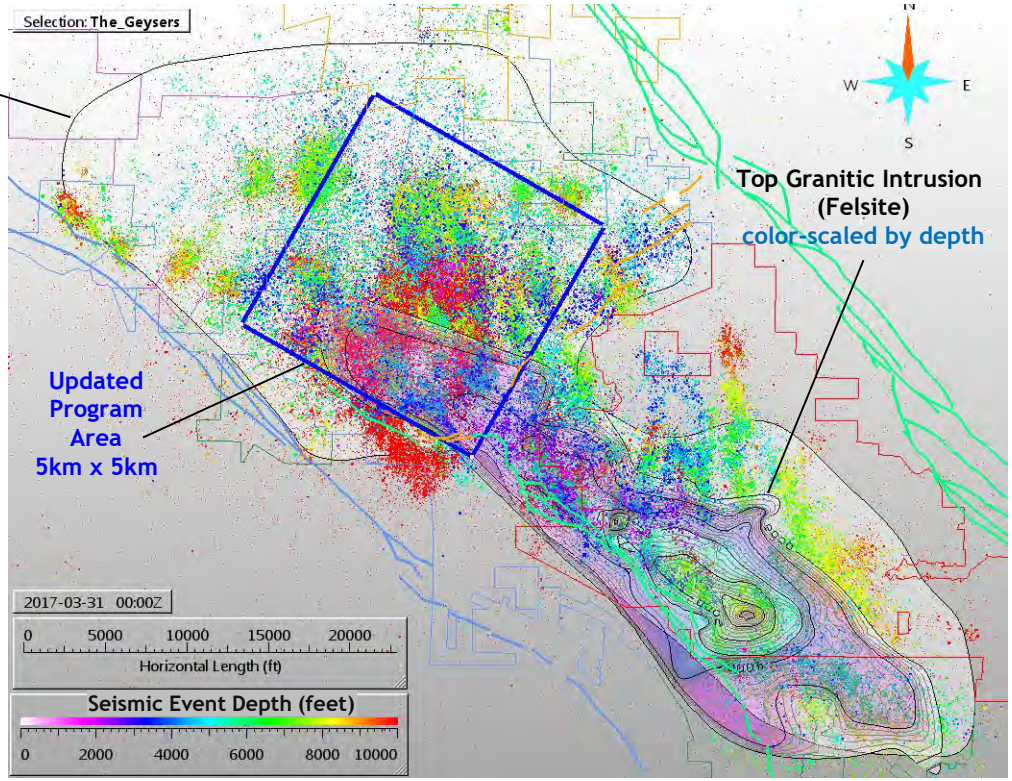
Project Partners

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

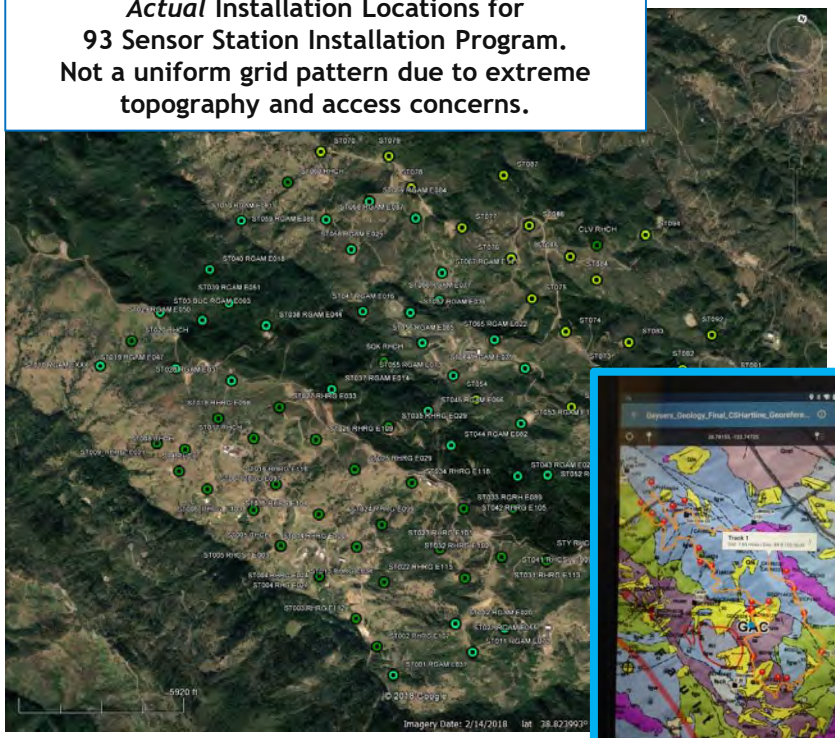
An extensive seismic sensor test program was planned and is being conducted with the project scientists.

Calpine Corporation has provided:

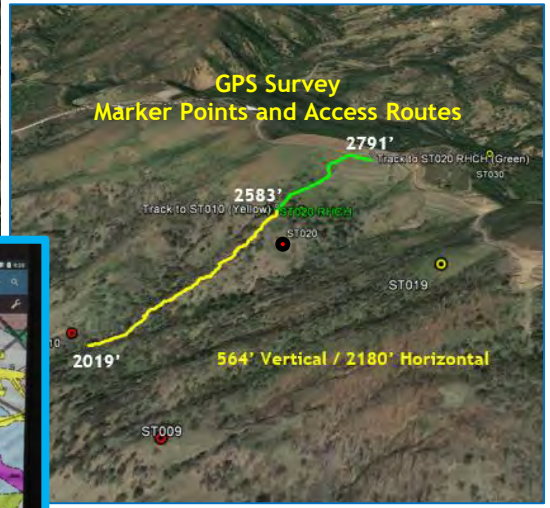
- The field location for this program.
- Technical support with survey design planning.
- On-site assessments including GPS surveying with updated equipment and techniques.
- Assistance to LBNL Contractor Ramsey Haught during 17 seismic sensor test installations.
- Coordination and updating of GPS surveys/maps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