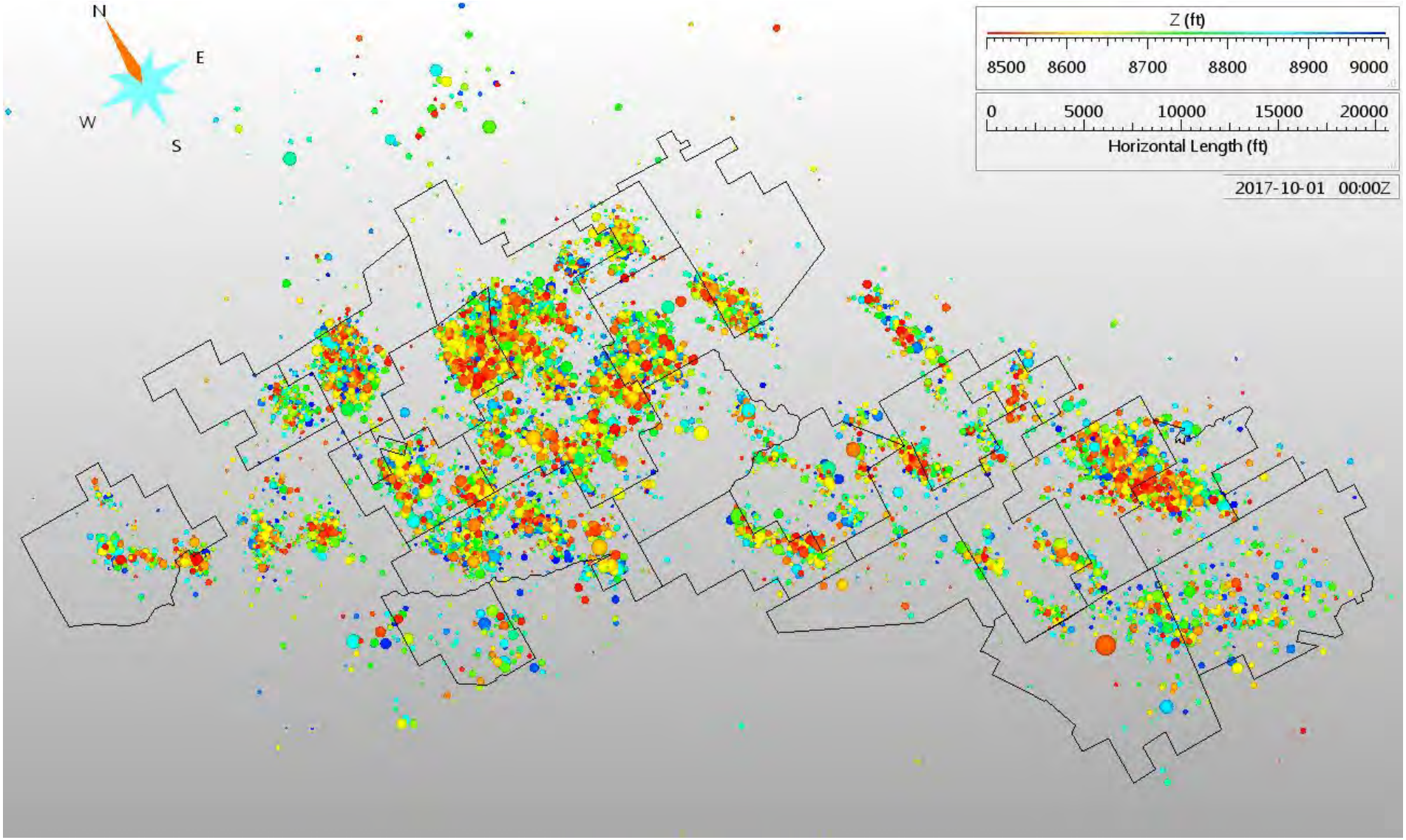
Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

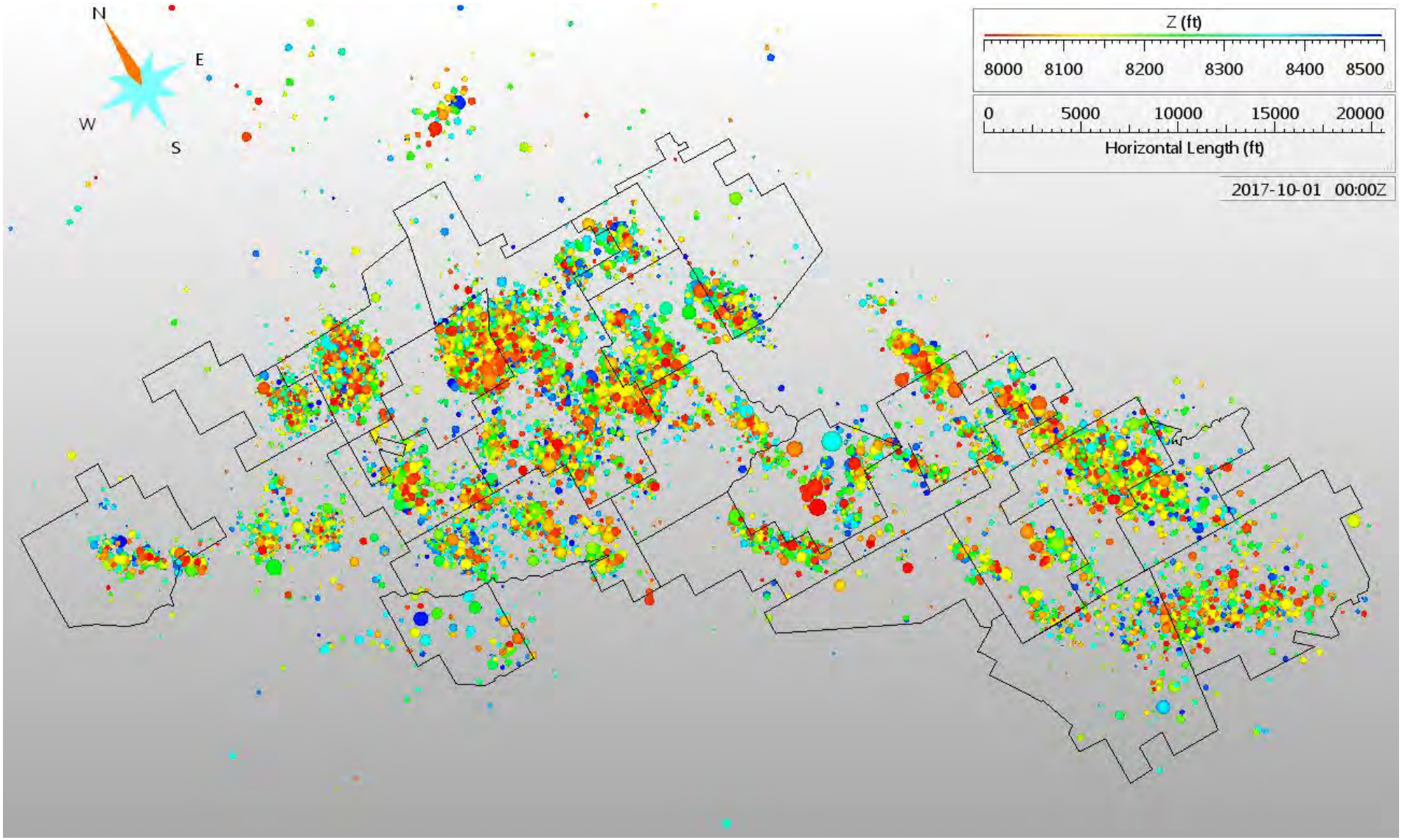
Depth Slice 8500 to 9000 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

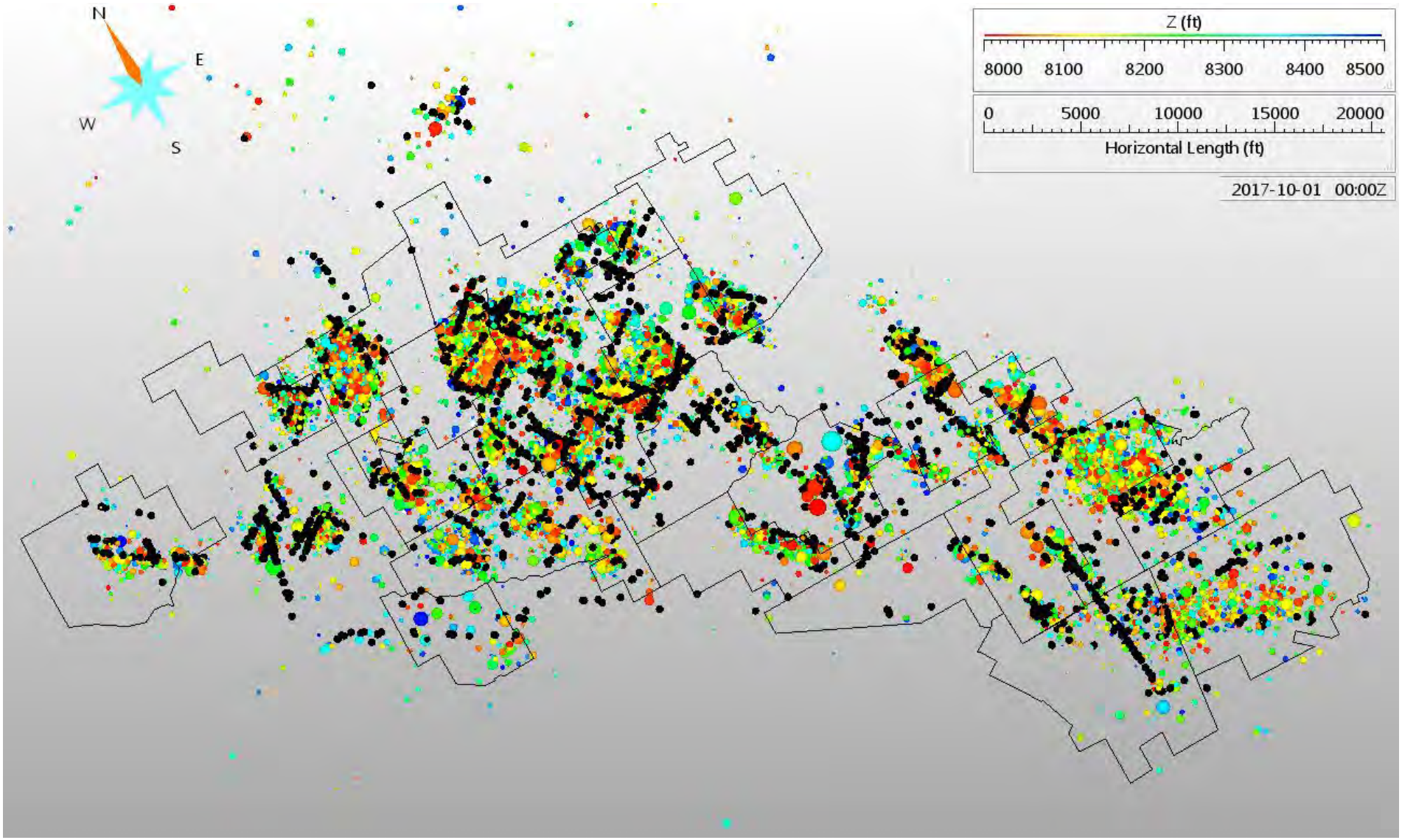
Depth Slice 8000 to 8500 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

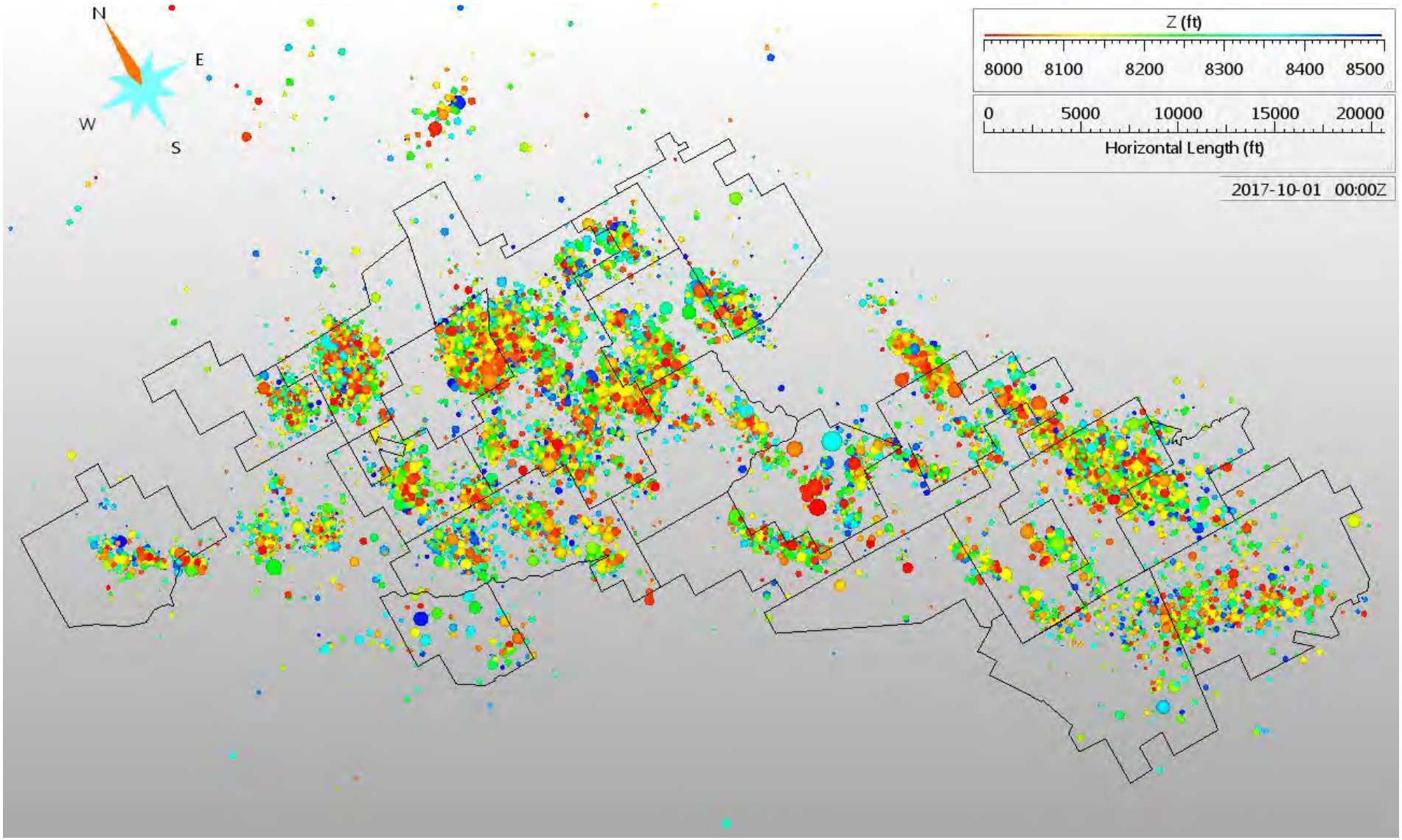
Depth Slice 8000 to 8500 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

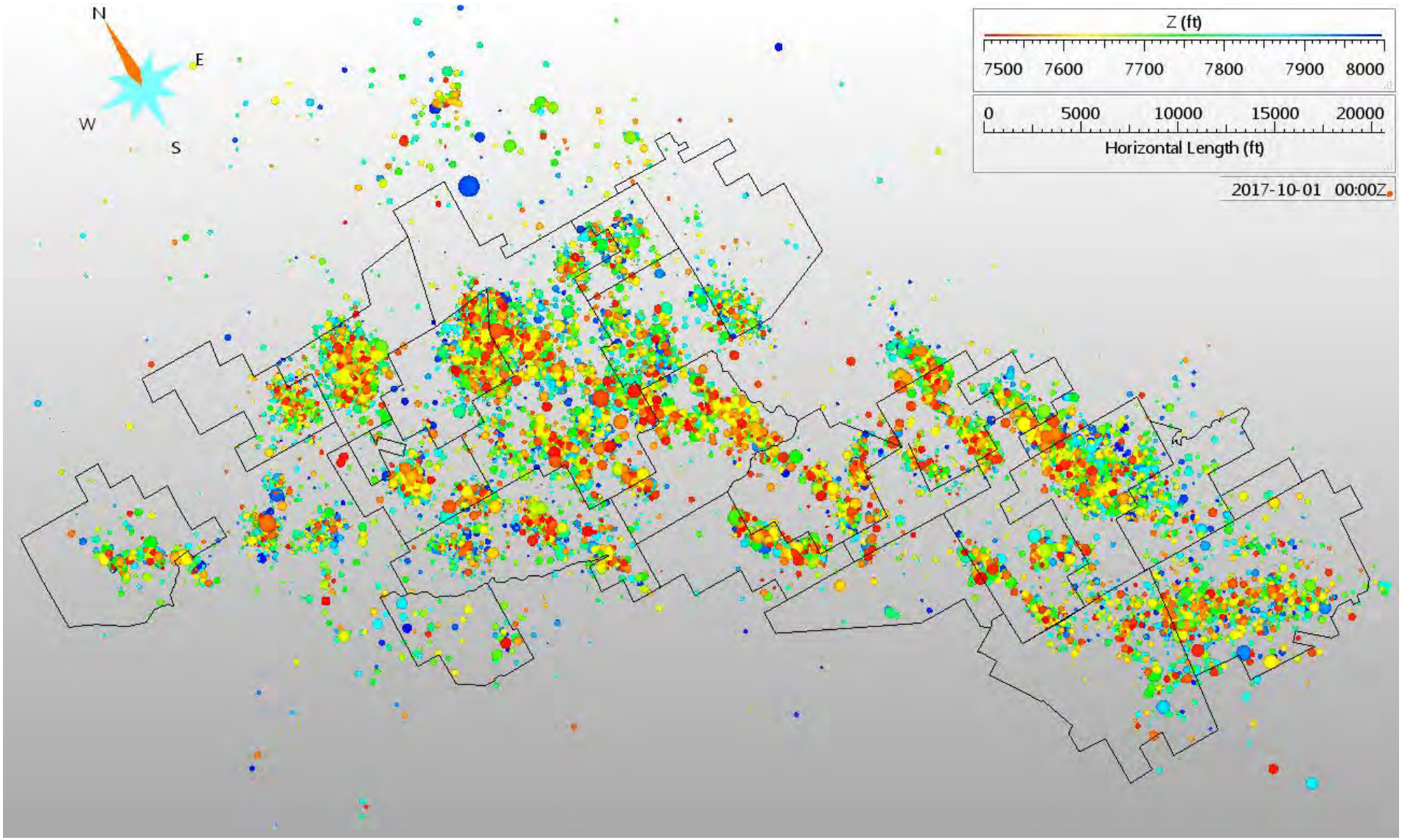
Depth Slice 8000 to 8500 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

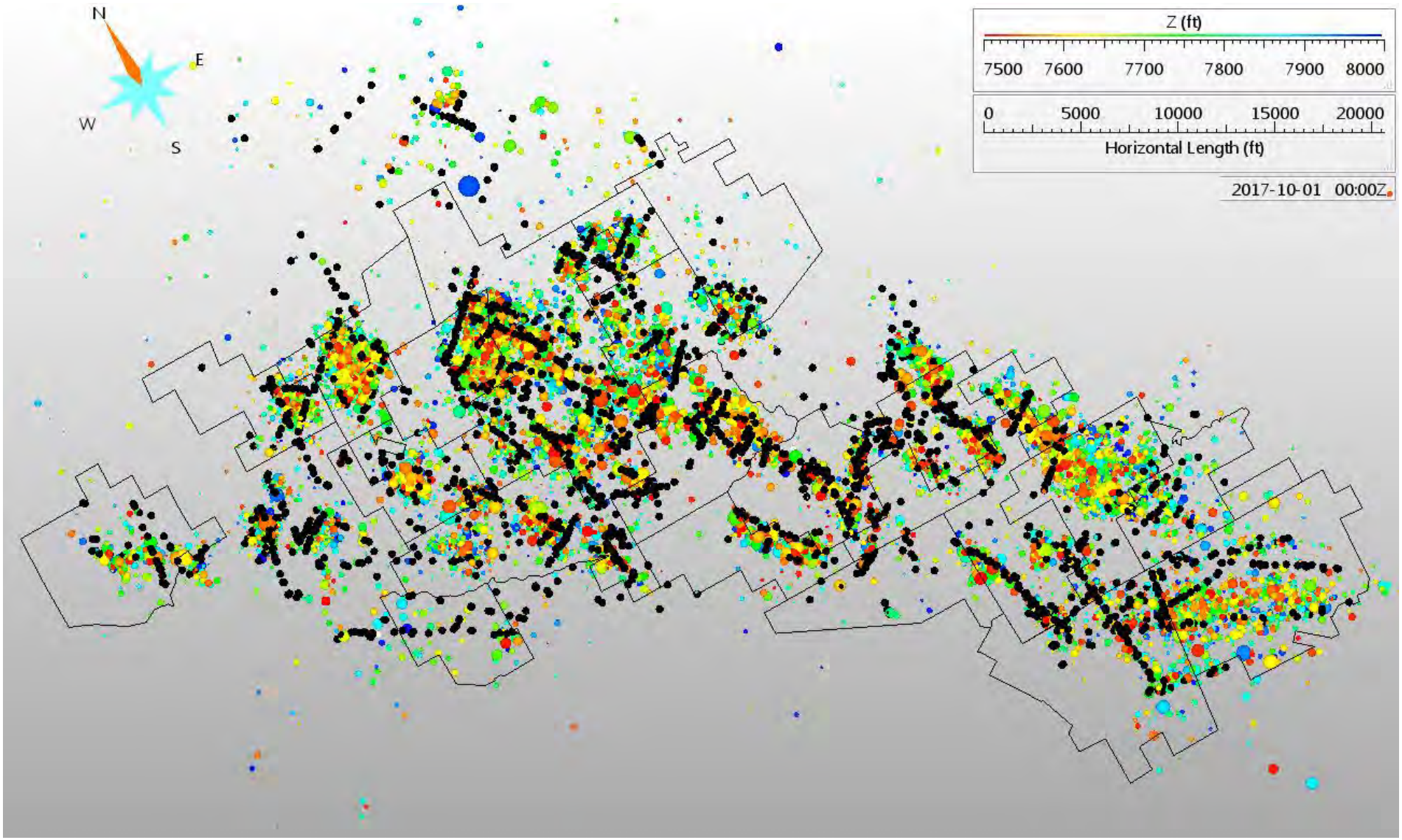
Depth Slice 7500 to 8000 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

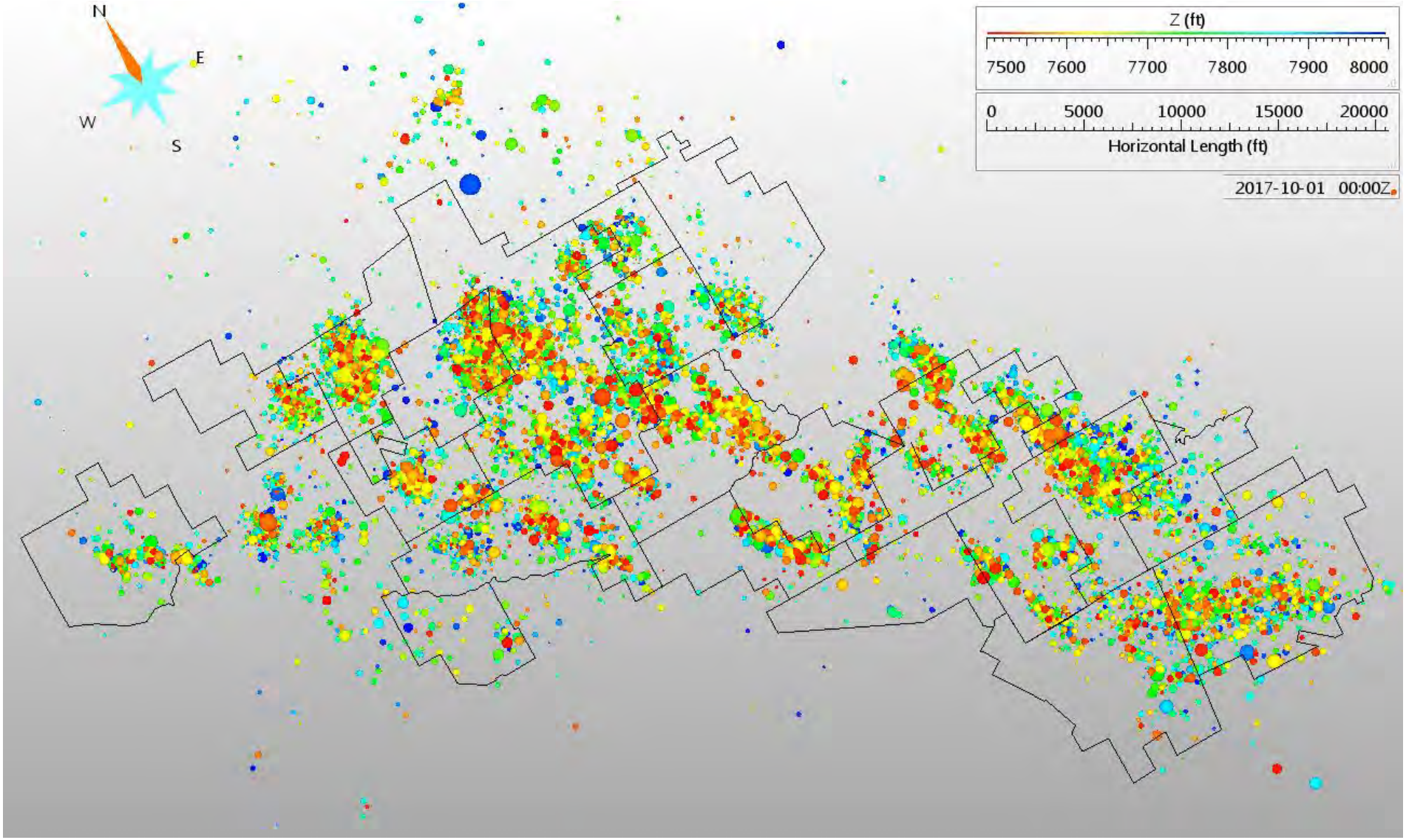
Depth Slice 7500 to 8000 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

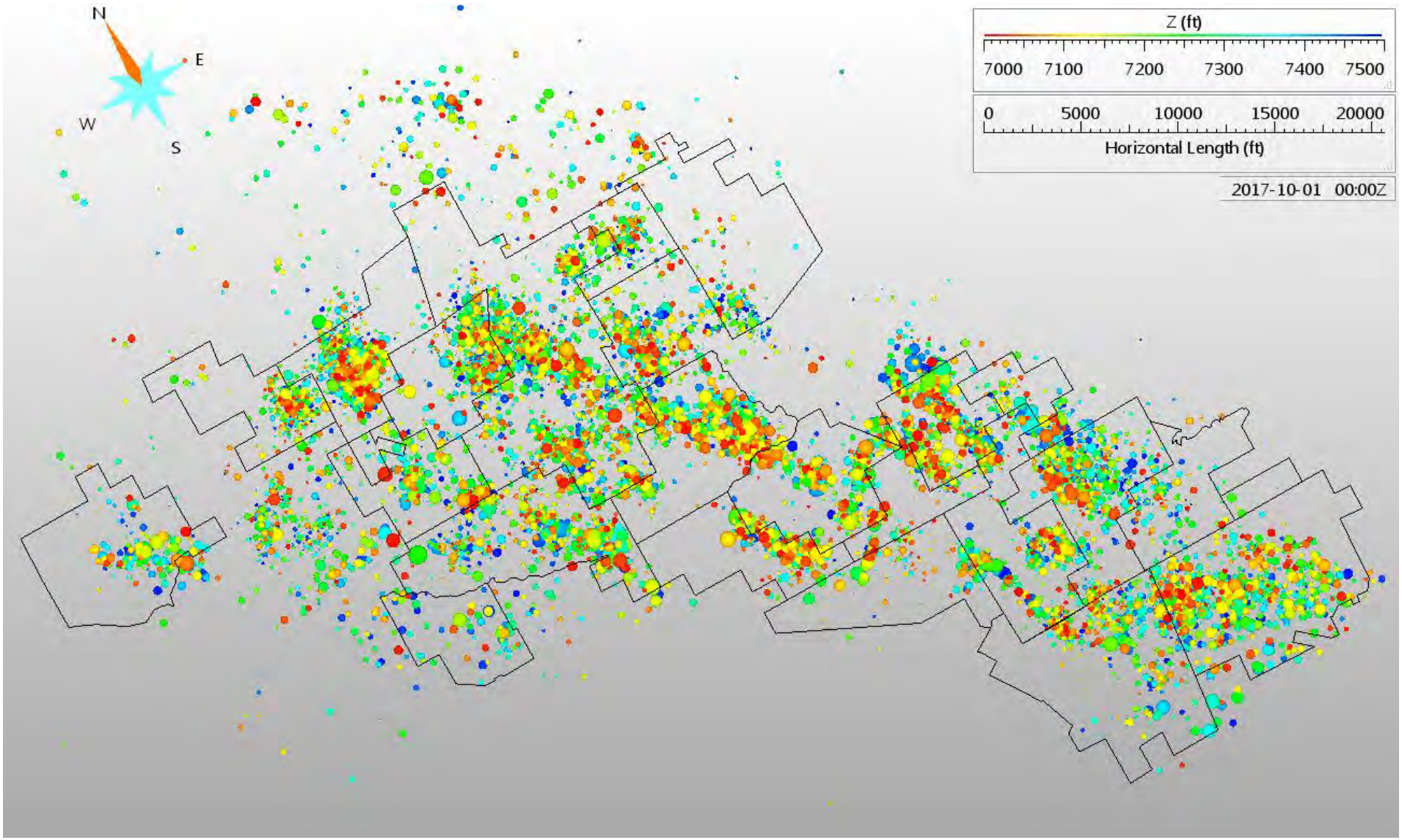
Fault/Fracture Analysis and Interpretation

Depth Slice 7500 to 8000 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

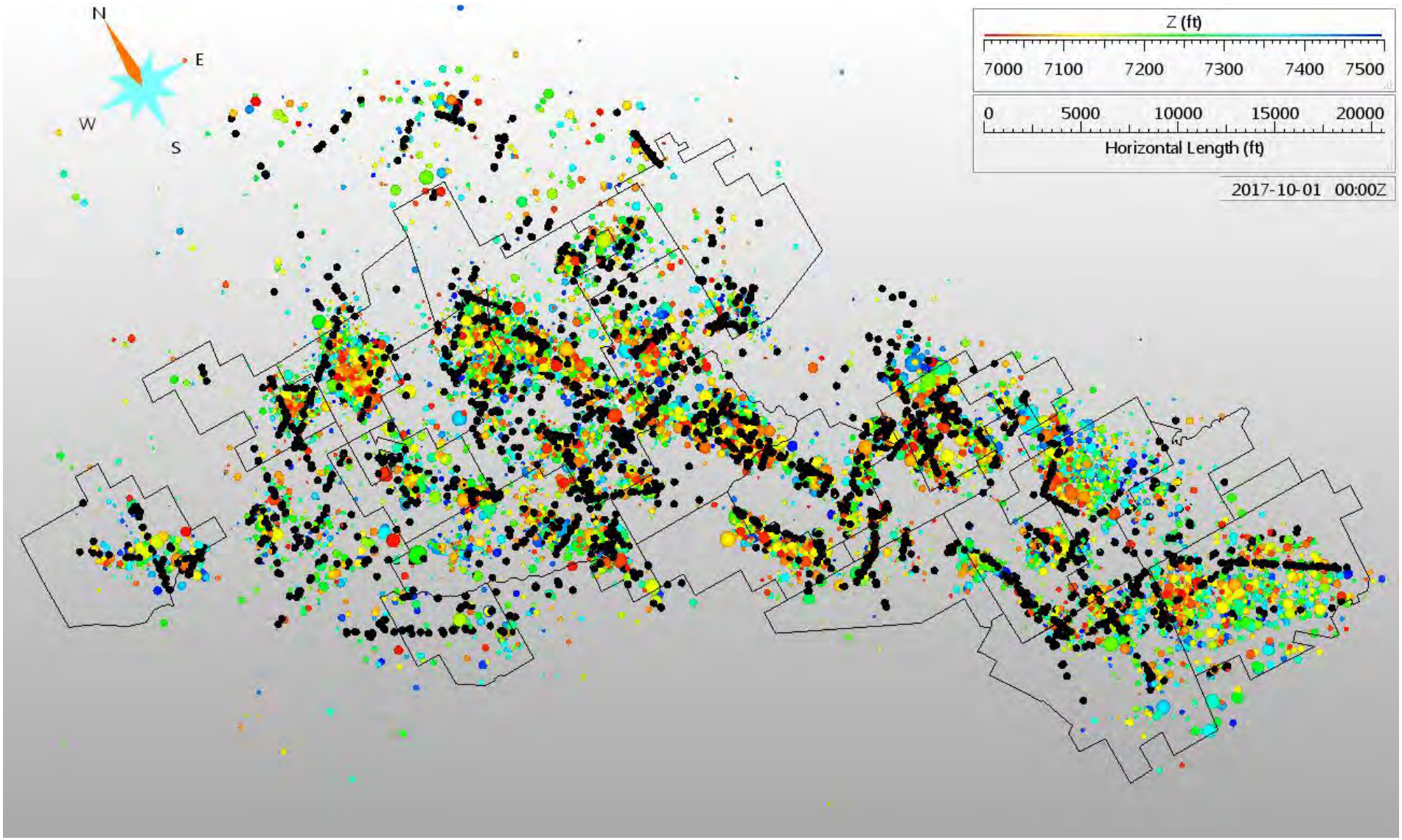
Fault/Fracture Analysis and Interpretation
Depth Slice 7000 to 7500 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

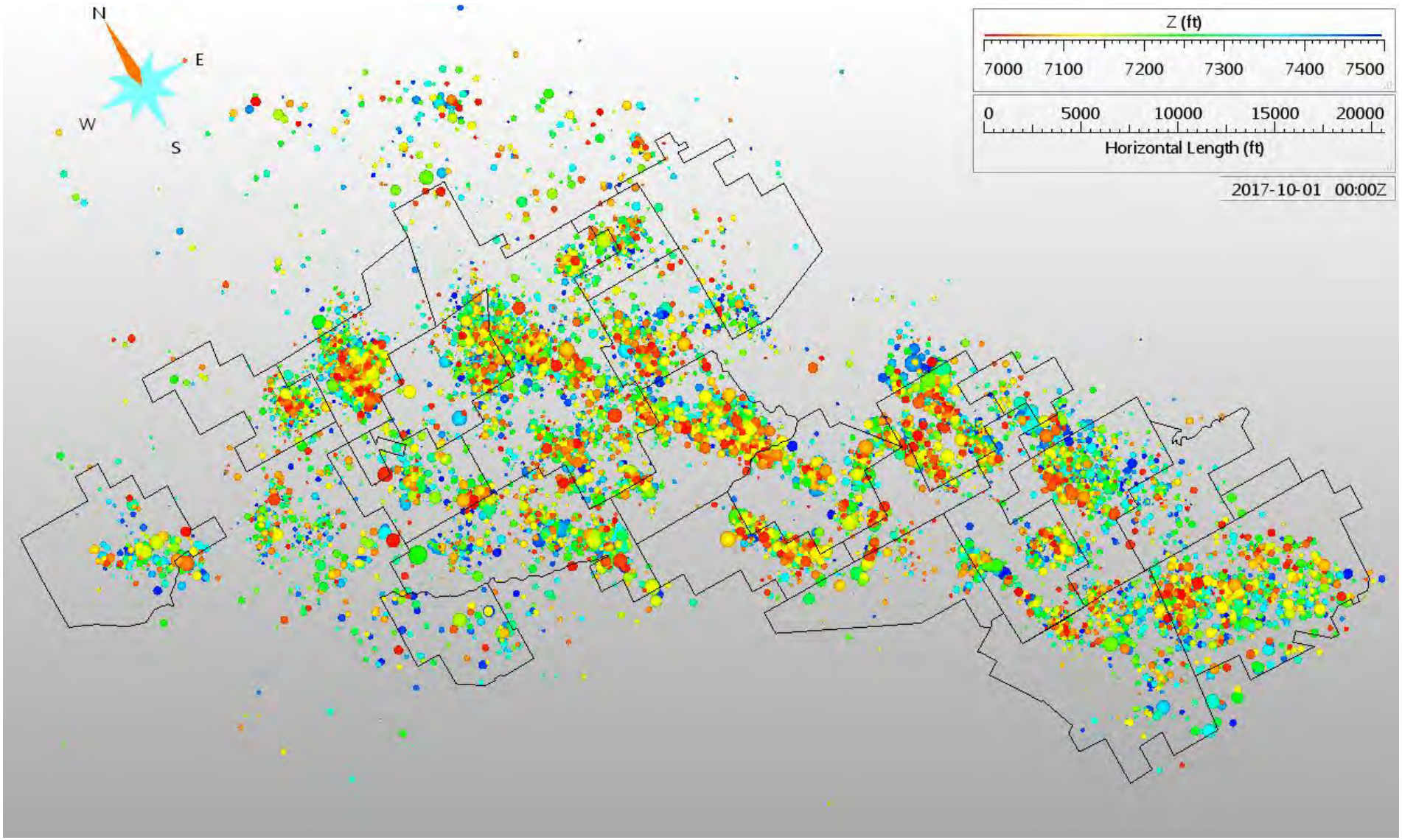
Depth Slice 7000 to 7500 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

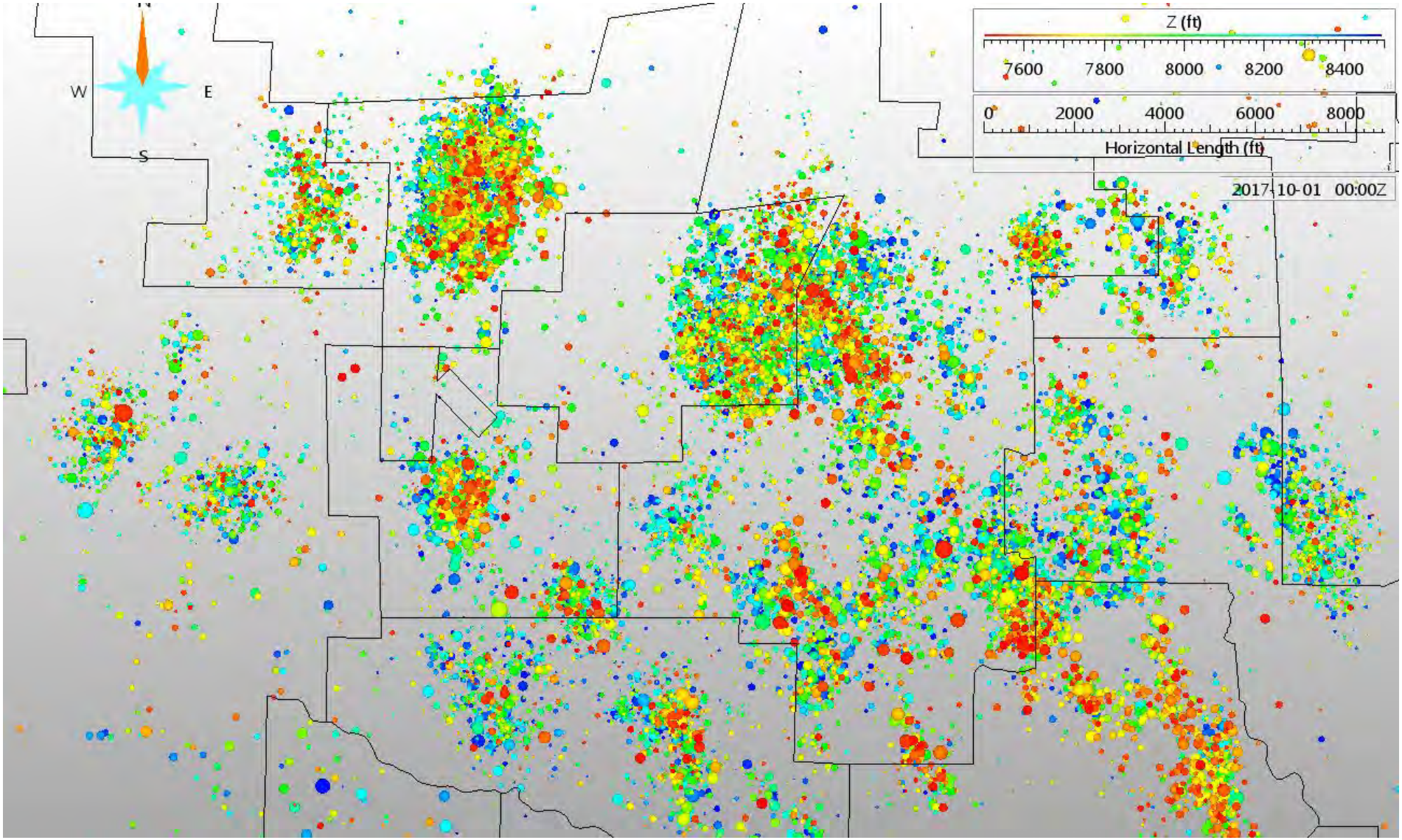
Depth Slice 7000 to 7500 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

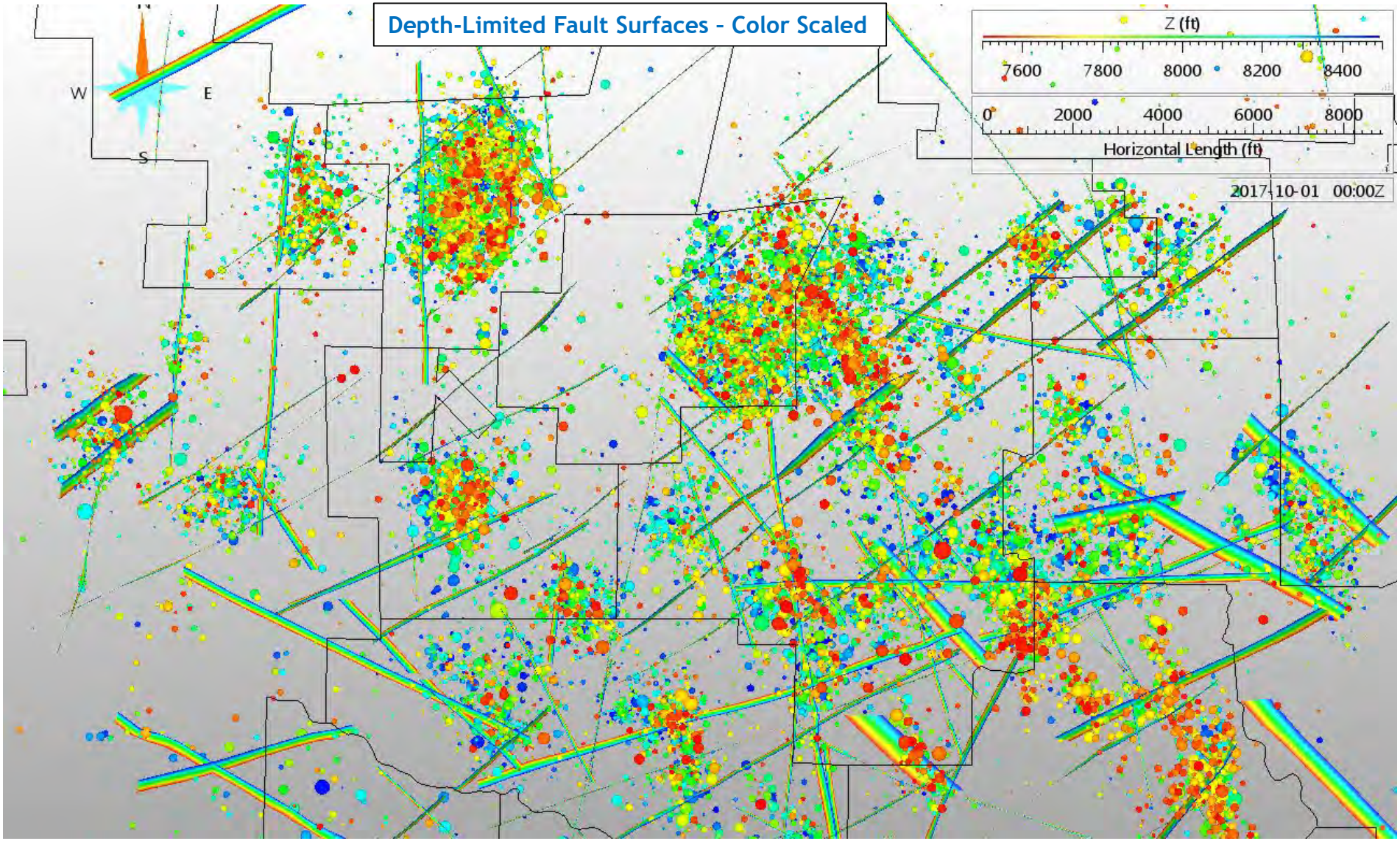
Depth Slice 7500 to 8500 Feet Subsea



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

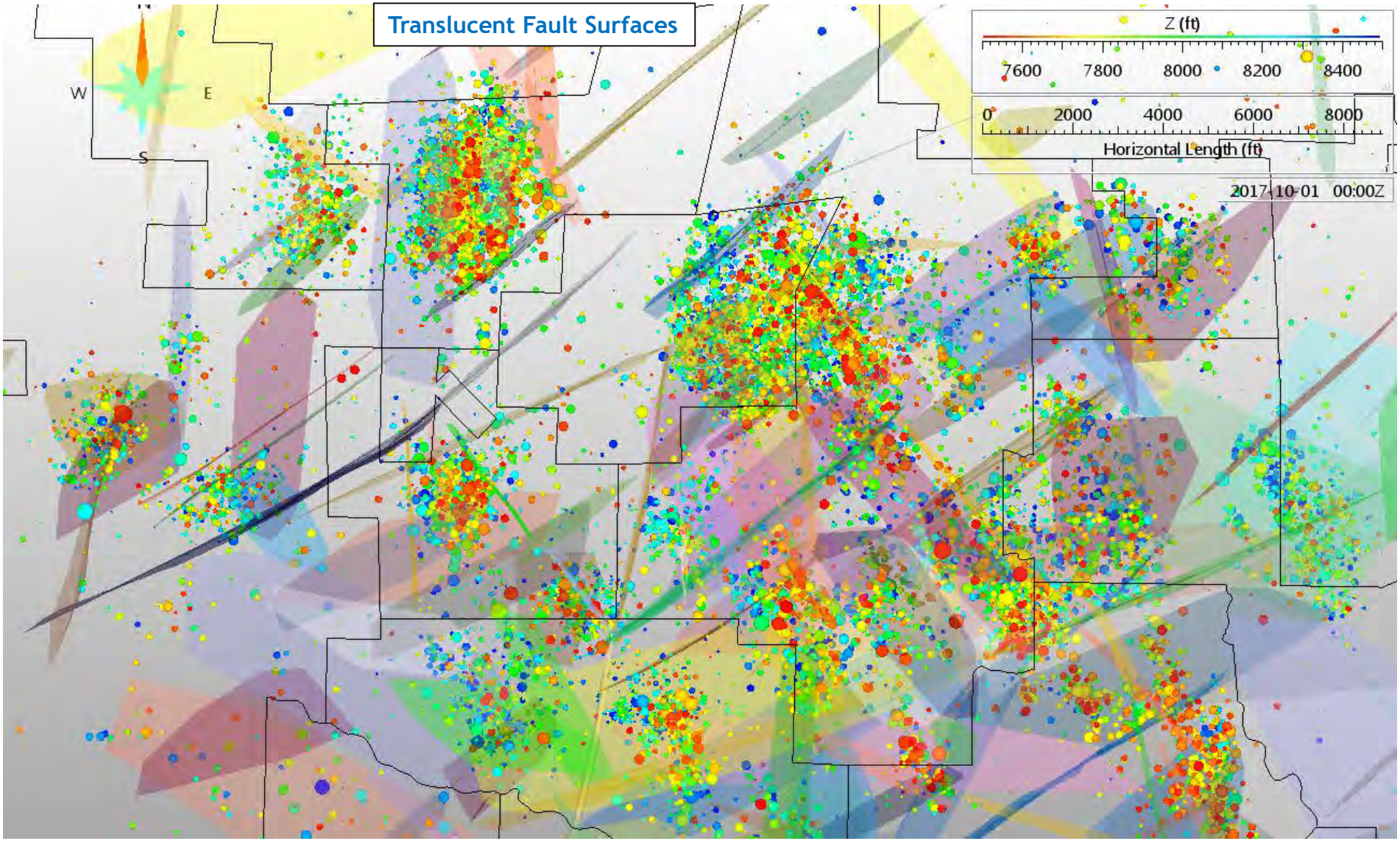
Depth Slice 7500 to 8500 Feet Subsea – North Geysers



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

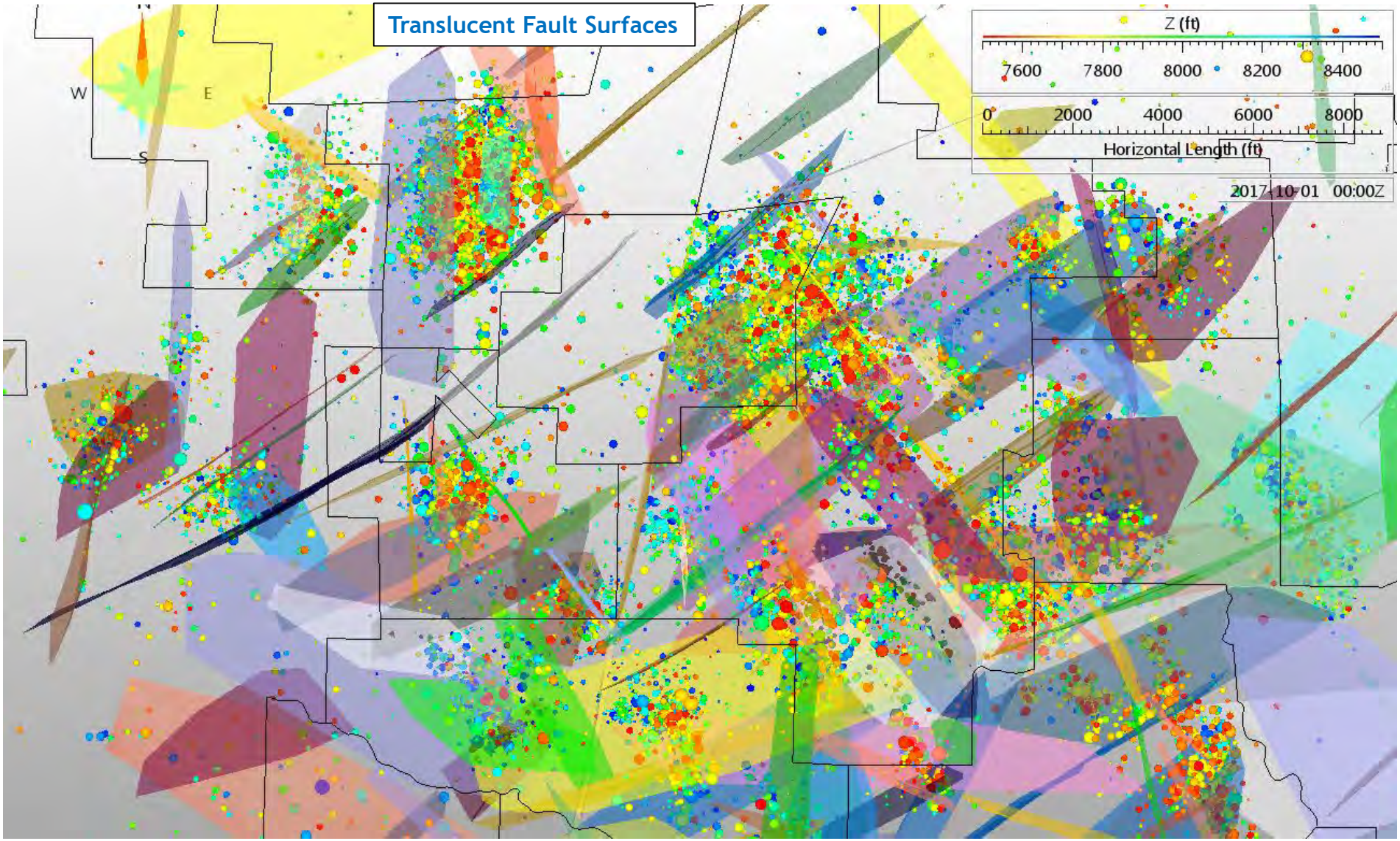
Depth Slice 7500 to 8500 Feet Subsea - North Geysers



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

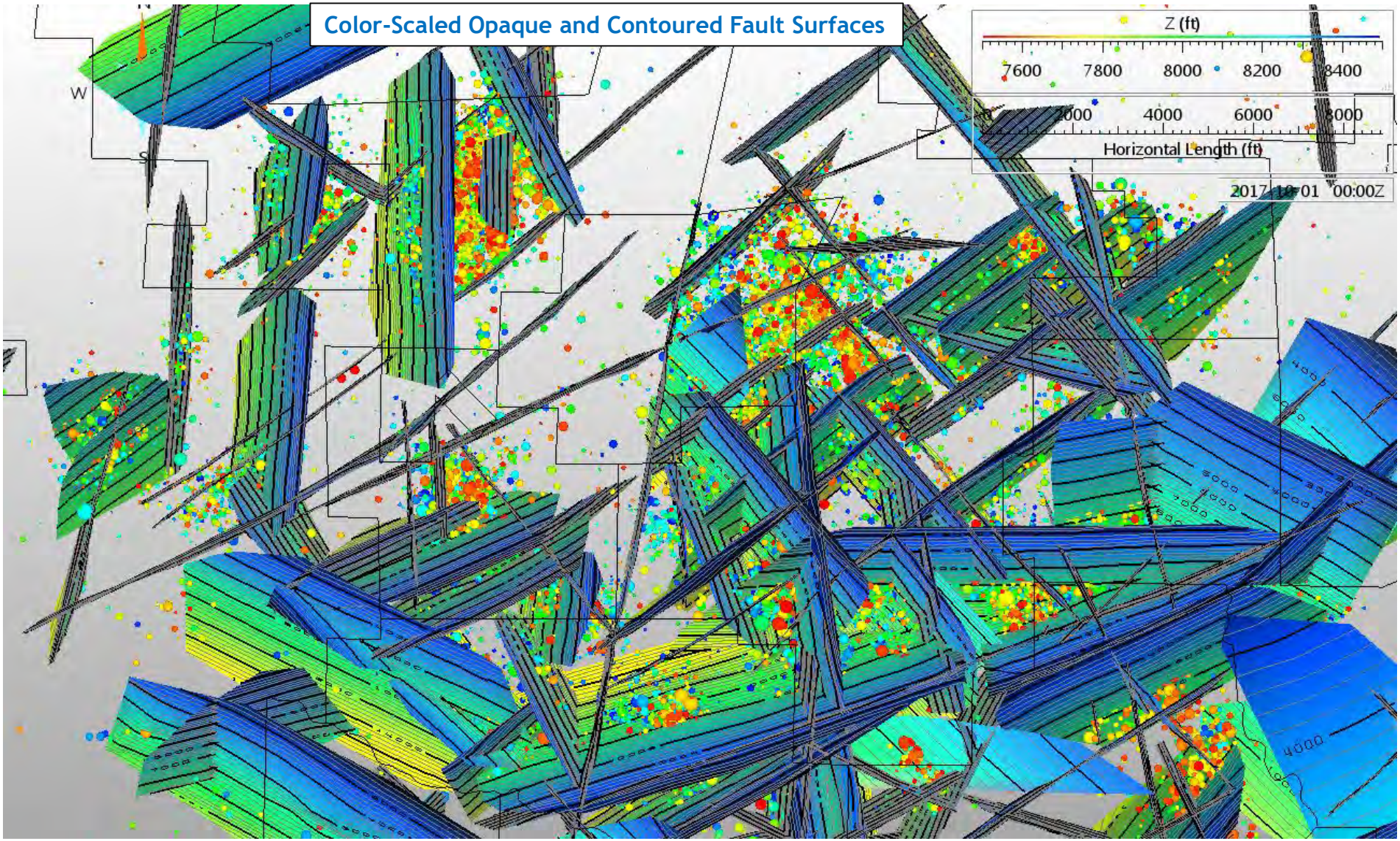
Depth Slice 7500 to 8500 Feet Subsea - North Geysers



Seismic Monitoring Advisory Committee Meeting

Fault/Fracture Analysis and Interpretation

Depth Slice 7500 to 8500 Feet Subsea



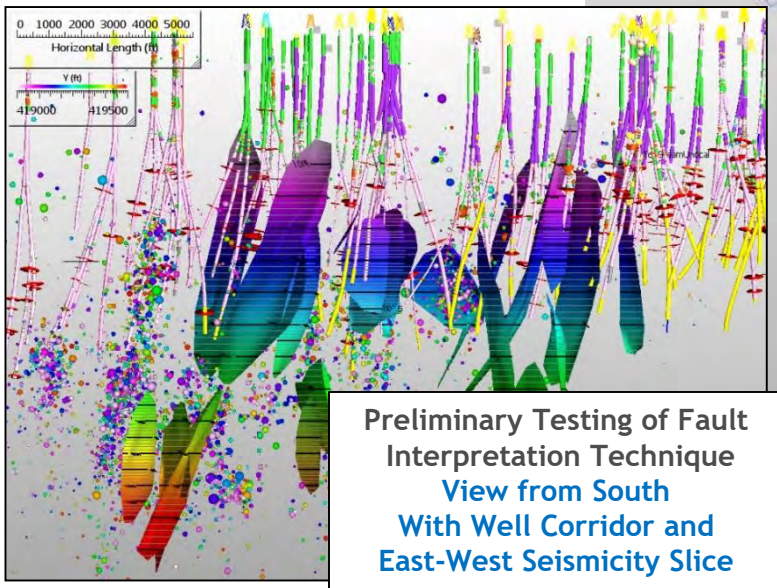
Seismic Monitoring Advisory Committee Meeting

3D Structural Model
Fault/Fracture Interpretation With Seismicity Slices

232 Refined Fault/Fracture Surfaces
From 26,709 individually interpreted points
Using 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)



Preliminary Testing of Fault Interpretation Technique
View from South
With Well Corridor and
East-West Seismicity Slice

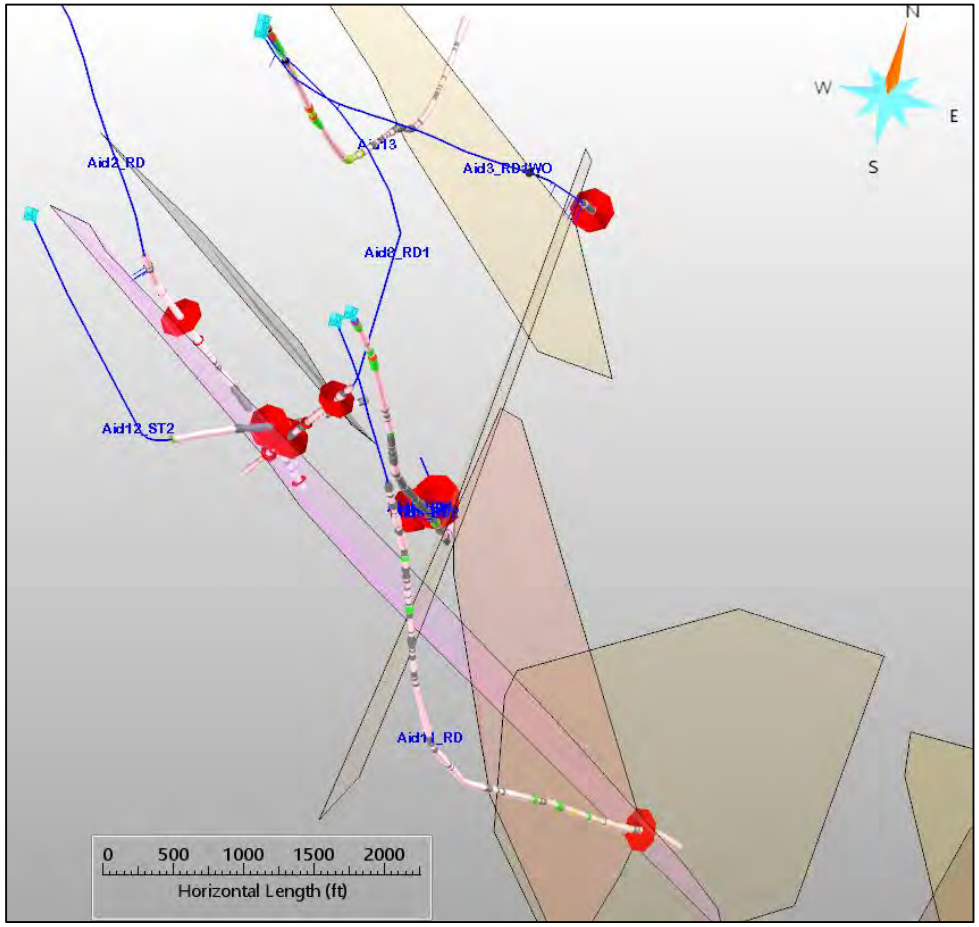
Seismic Monitoring Advisory Committee Meeting

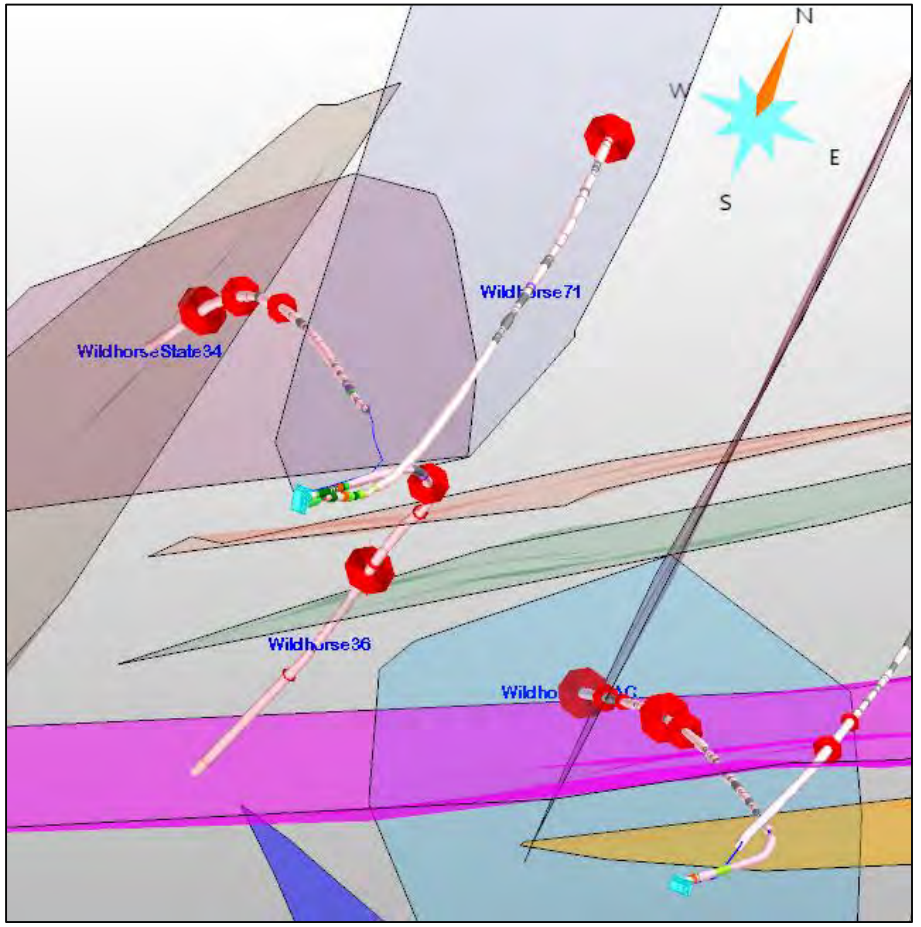
3D Fault Interpretation

Steam Entries vs. Interpreted Fracture Surfaces (Unbiased)

Aidlin Area (left) and Wildhorse Area (right)

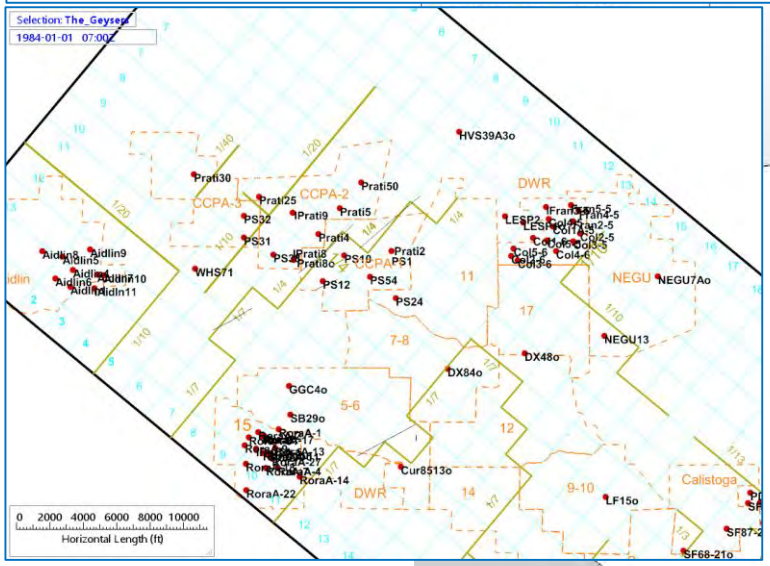
The majority of significant steam entries for the injection wells shown occur at *approximately* the intersection with the interpreted fracture surfaces.

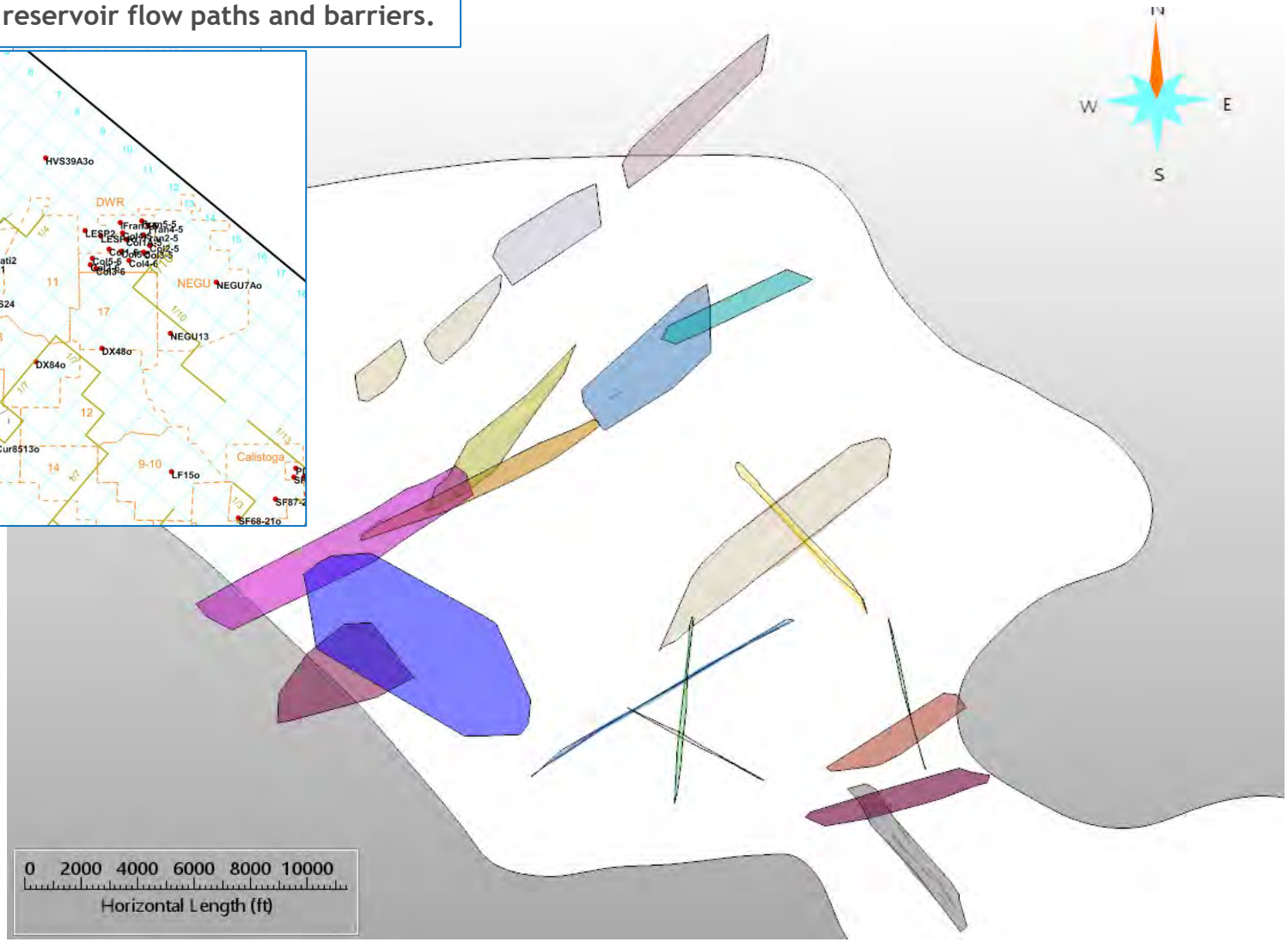




Seismic Monitoring Advisory Committee Meeting
3D Structural Model Building

Combinations of ***anastomosing fault surfaces*** or ***fault zones*** are consistent with the positions of previously identified steam reservoir compartments. These ***fault zones*** will be used to represent steam reservoir flow paths and barriers.





Seismic Monitoring Advisory Committee Meeting

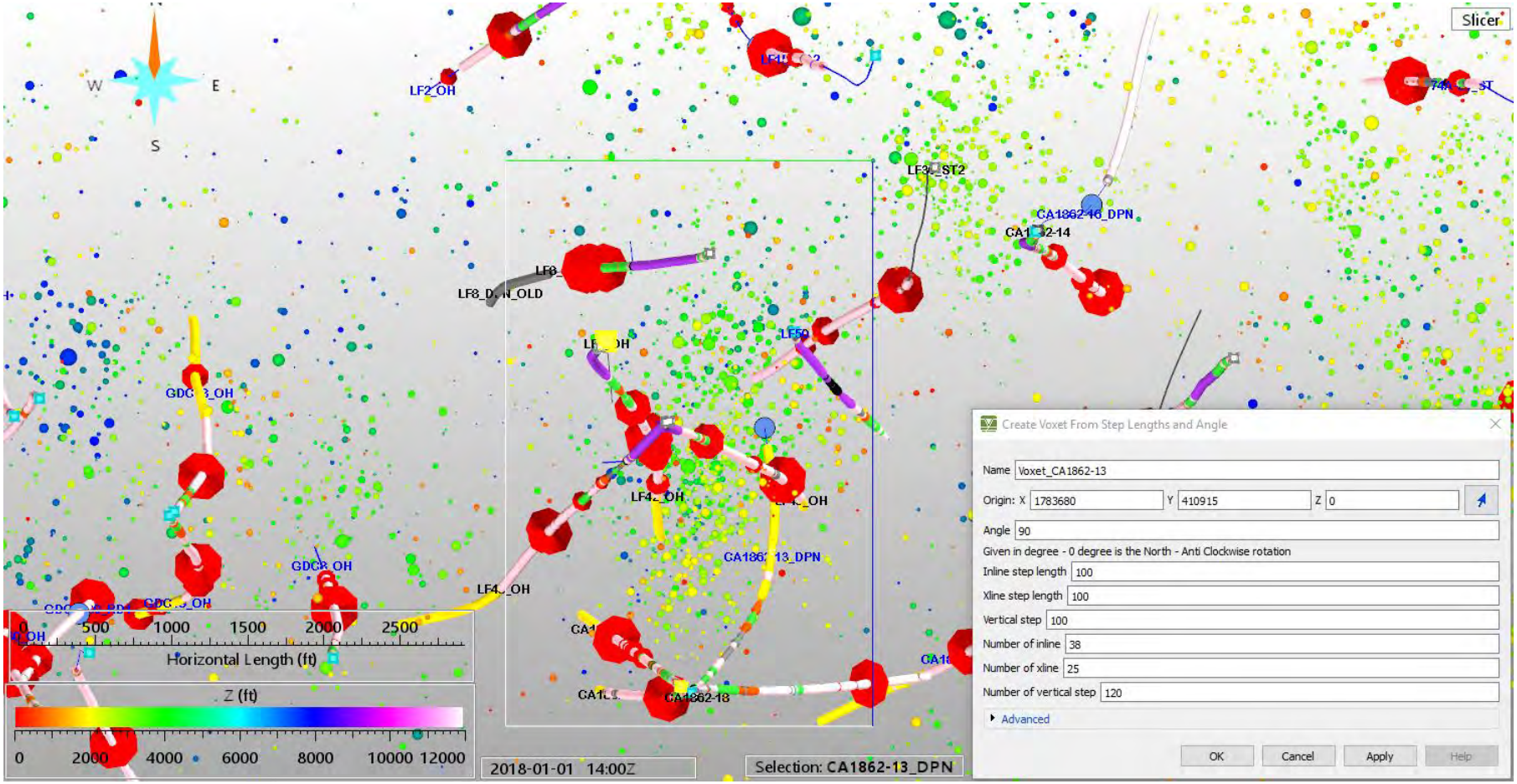
Injection Well CA1862-13

Induced Seismicity Analysis and Stimulated Rock Volume

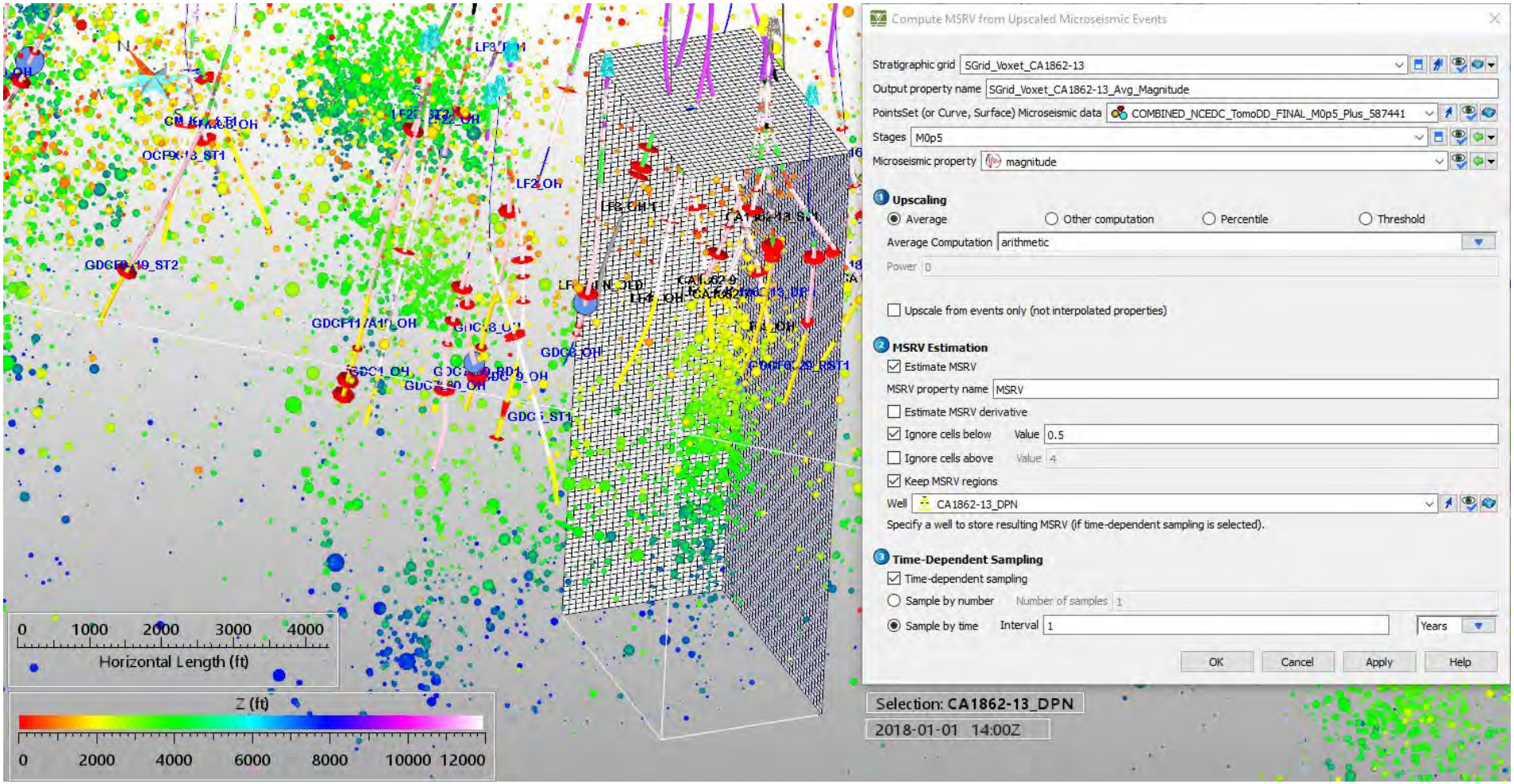
Oblique View from West-Northwest

Oblique View from South-Southeast

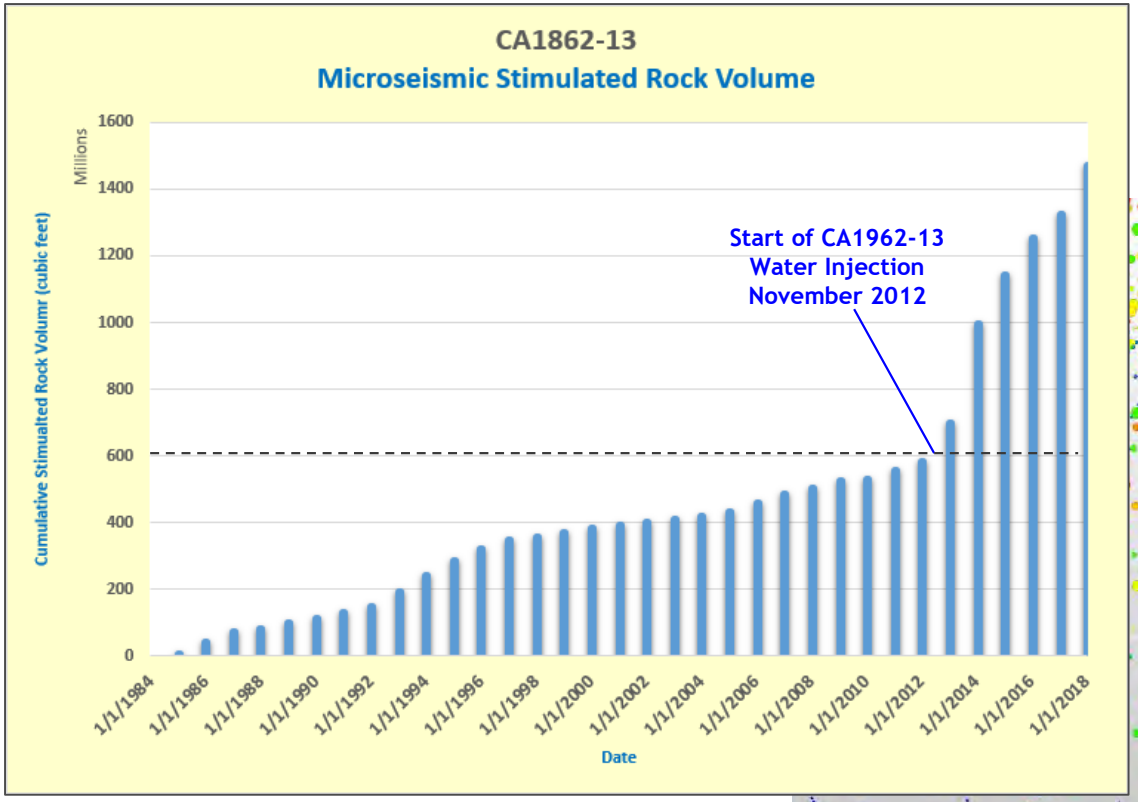
Map View

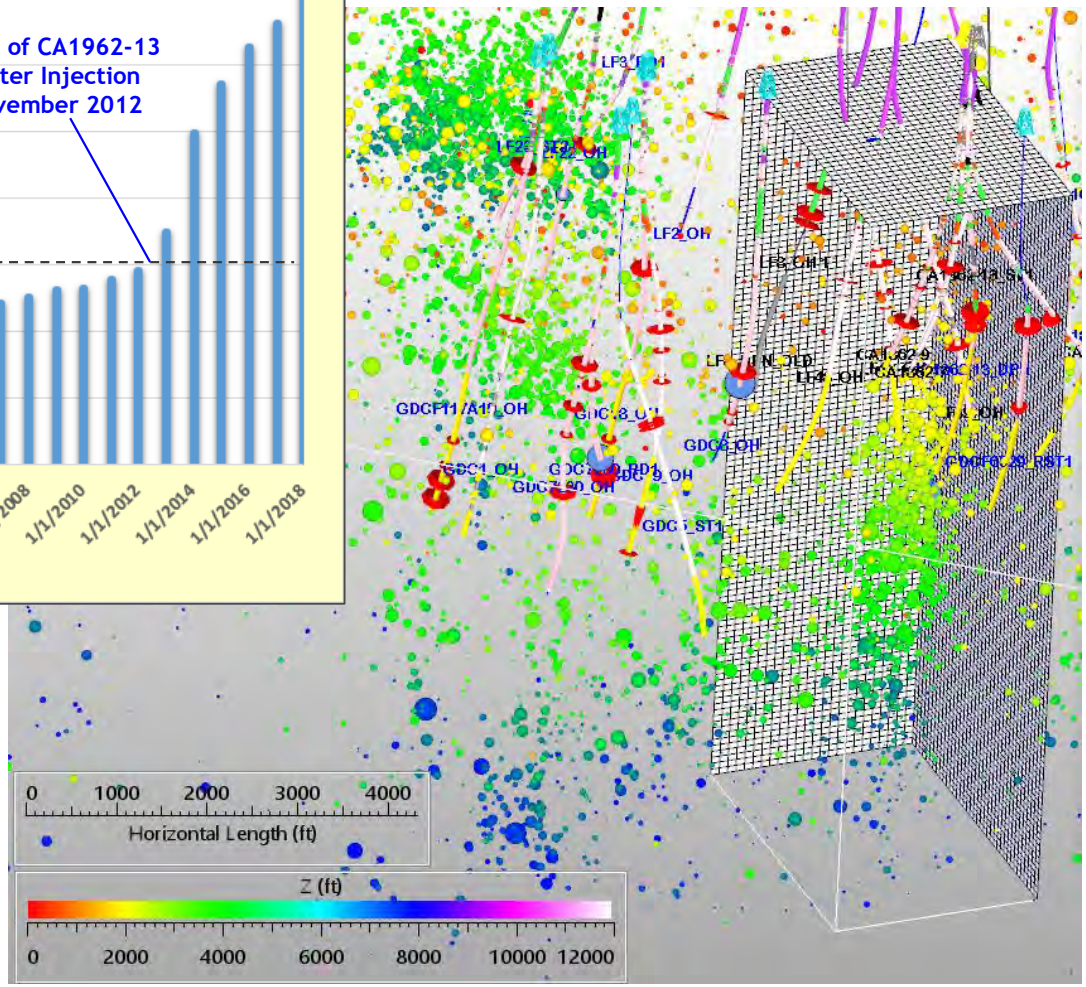


Seismic Monitoring Advisory Committee Meeting
Injection Well CA1862-13
Induced Seismicity Analysis and Stimulated Rock Volume



Seismic Monitoring Advisory Committee Meeting
Injection Well CA1862-13
Induced Seismicity Analysis and Stimulated Rock Volume



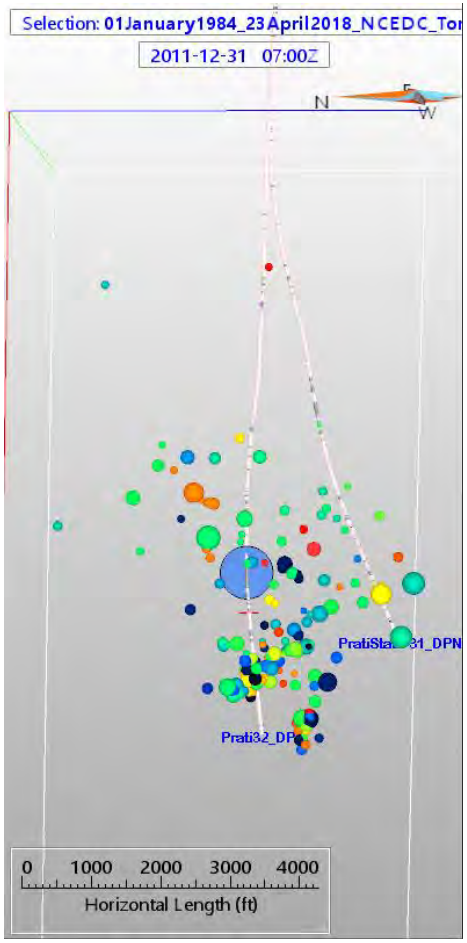


Seismic Monitoring Advisory Committee Meeting

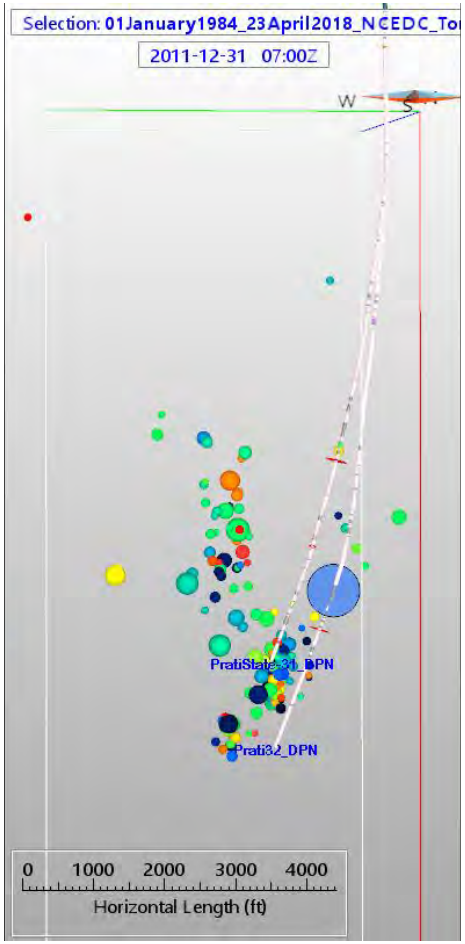
Injection Well Prati 32 Deepen

Seismicity Animation Weekly From 01 October 2011 to 31 December 2011

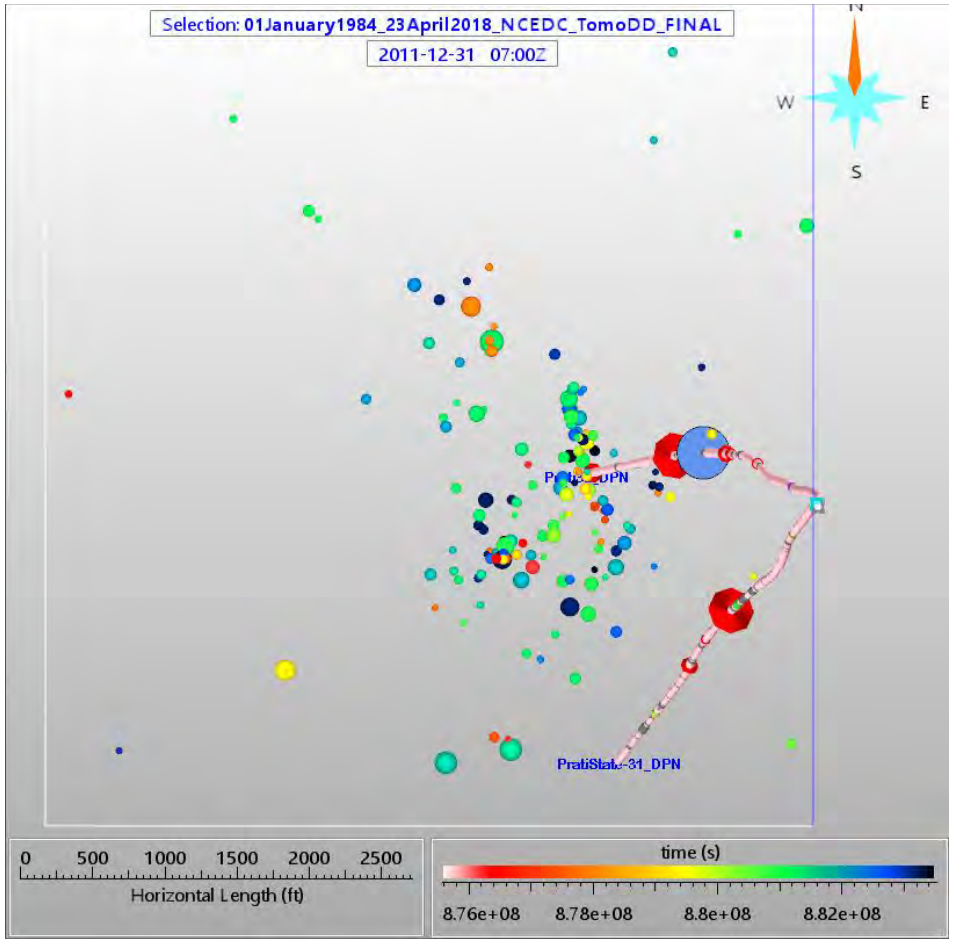
Oblique View from West-Northwest



Oblique View from South-Southeast

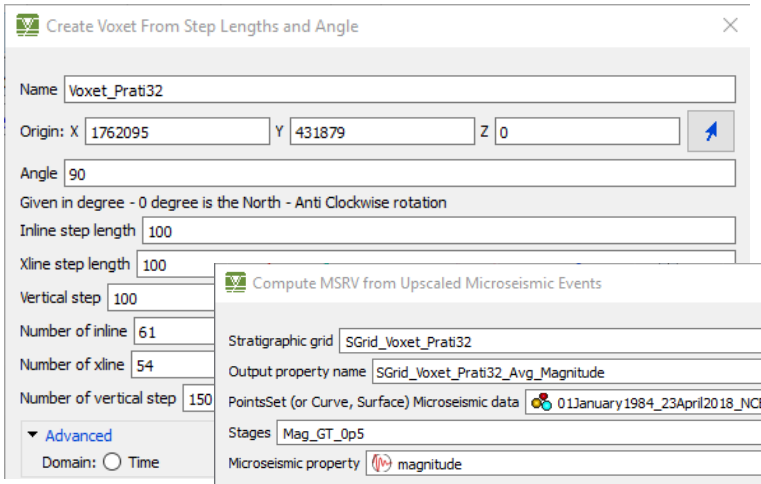


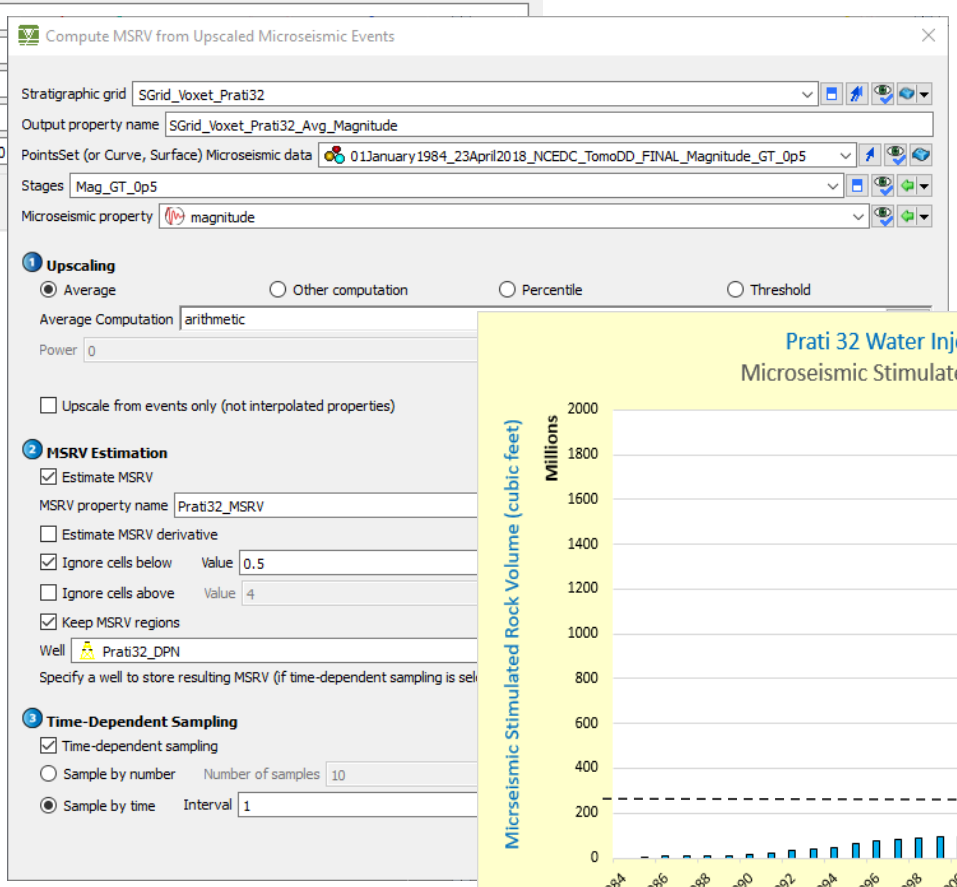
Map View

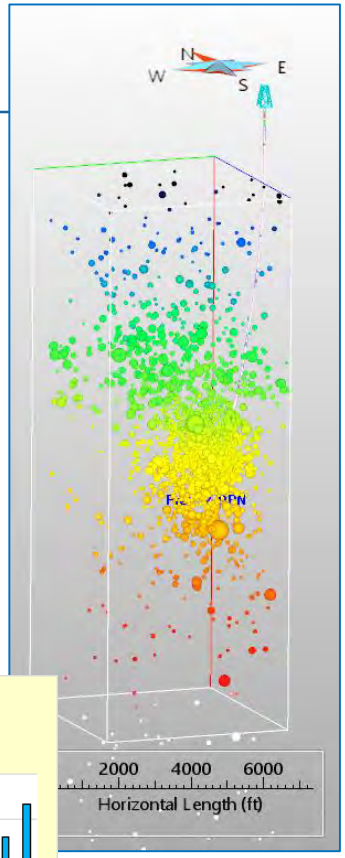


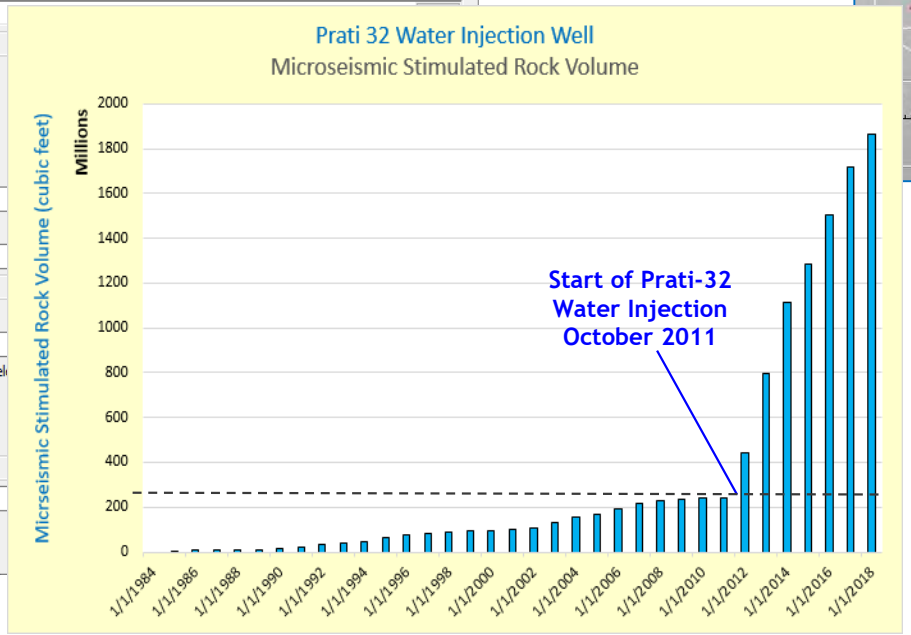
Time Range One 875,577,600 To 883,526,400 Seconds; Water Volumes Are Verified Monthly Volumes At Months End

Seismic Monitoring Advisory Committee Meeting
Injection Well Prati 32
Microseismic Stimulated Rock Volume









Seismic Monitoring Advisory Committee Meeting
Injection Well Prati 32
Event Magnitude vs. Log (Frequency of Events M>/= X)

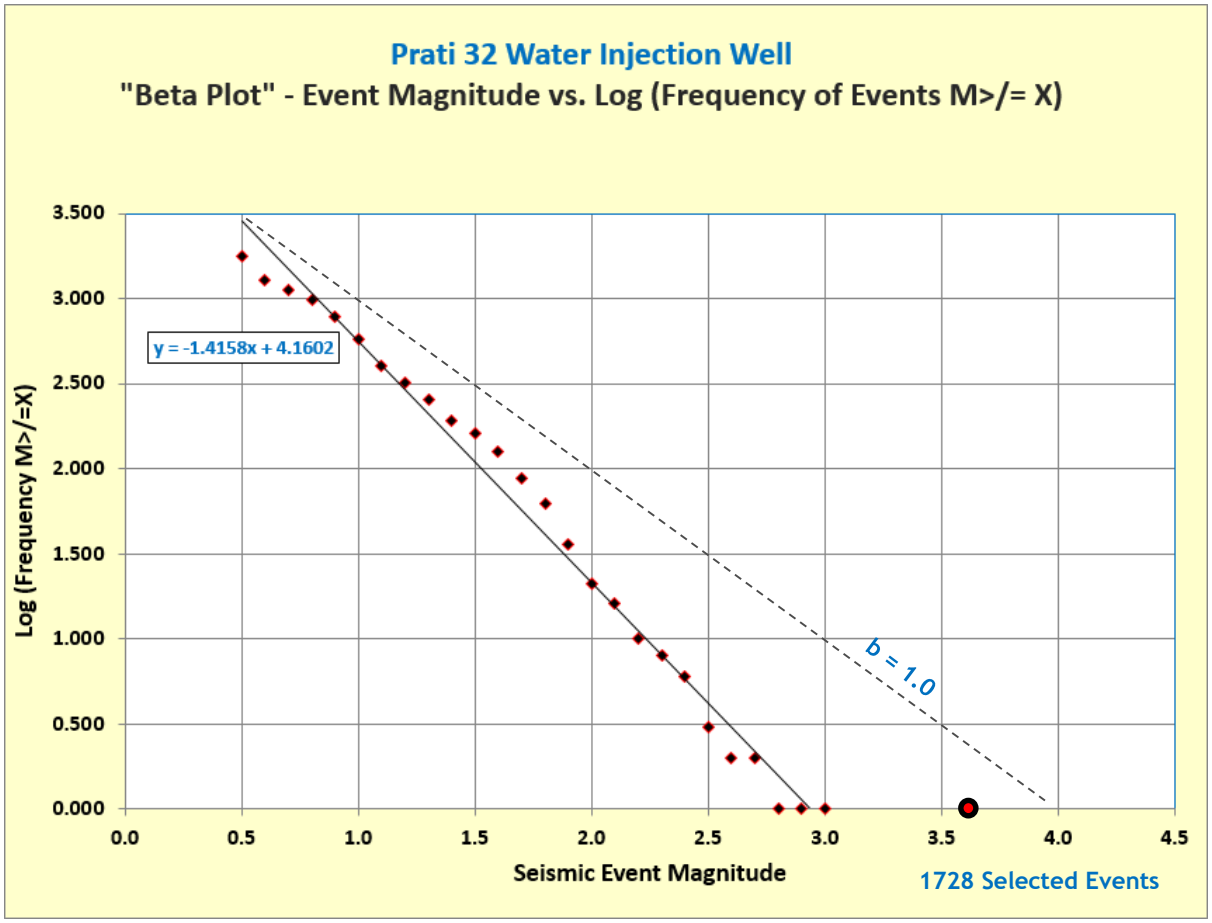
The Gutenberg-Richter law expresses the relationship between seismic event magnitude and total number of seismic events in any given region and time period.

$\log_{10}N = a - bM$

Where:

N is the number of events having a magnitude > M

a and b are constants; b is generally close to 1.0 for natural seismicity



Maximum Event Magnitude:
3.67
Injection

Seismic Monitoring Advisory Committee Meeting
Injection Well CA1862-13
Event Magnitude vs. Log (Frequency of Events M>/= X)

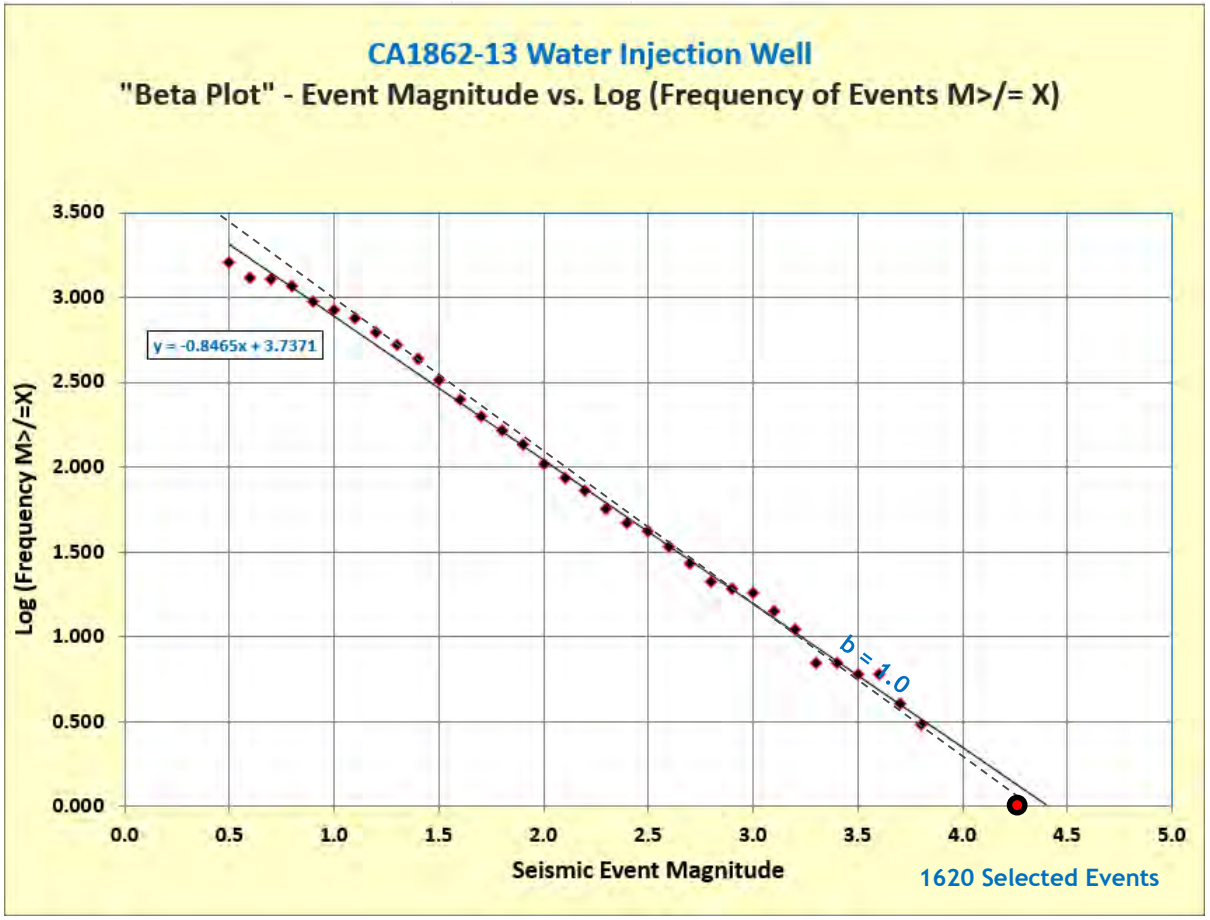
The Gutenberg-Richter law expresses the relationship between seismic event magnitude and total number of seismic events in any given region and time period.

$\log_{10}N = a - bM$

Where:

N is the number of events having a magnitude > M

a and b are constants; b is generally close to 1.0 for natural seismicity



Maximum Event Magnitude:
4.33
Pre-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

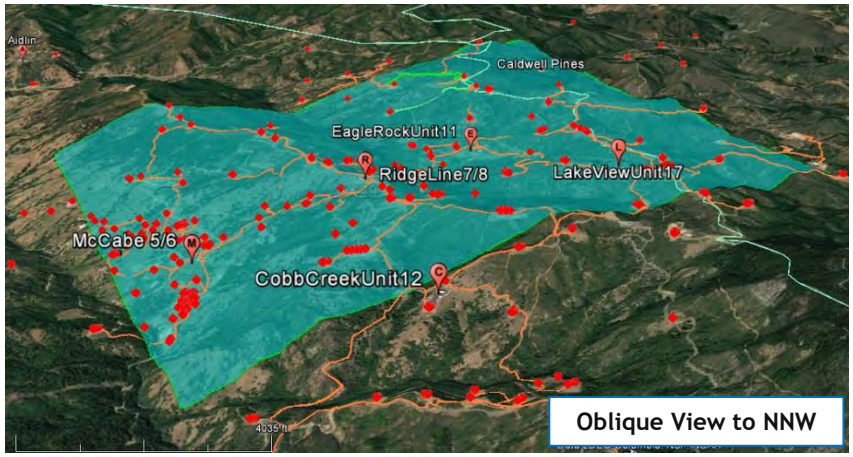
Lawrence Berkeley National Laboratory

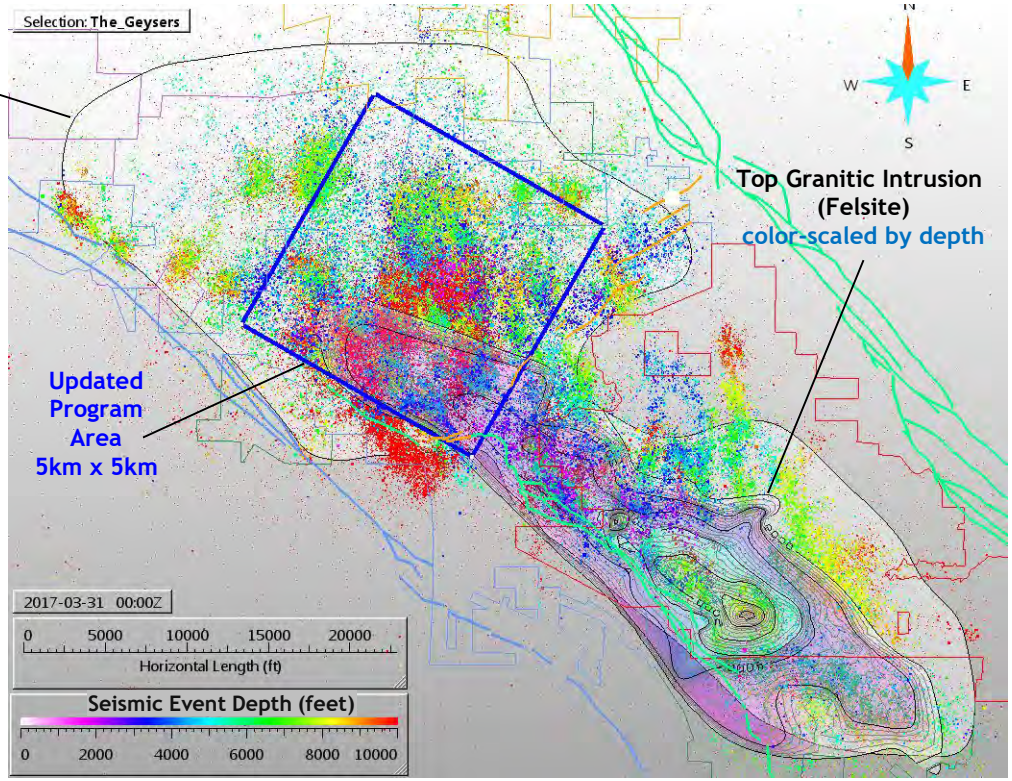
Project Partners

Calpine Corporation
Array Information Technology

California Energy Commission Funds Recommended

$1,672,639





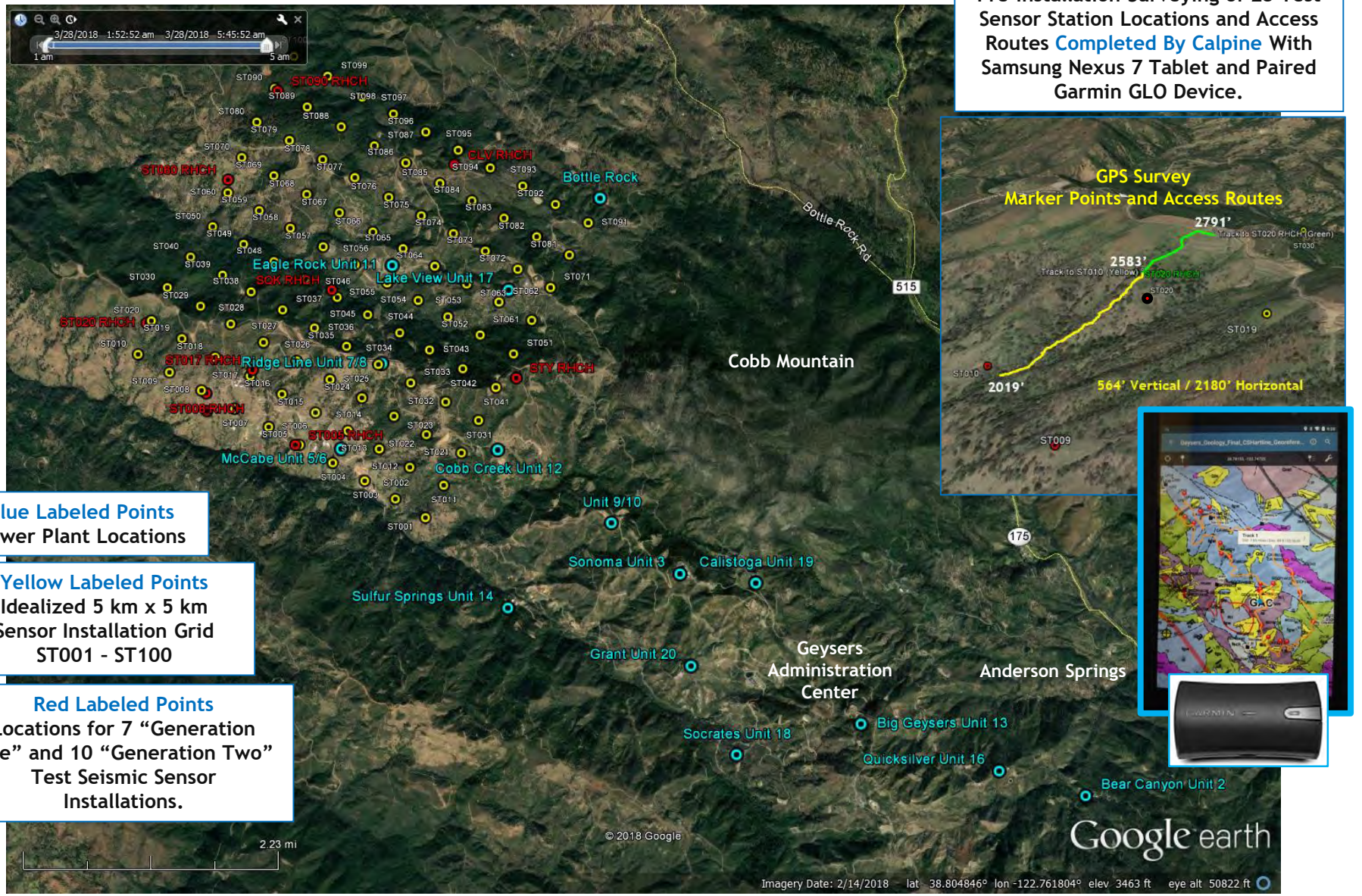
* Dr. Kurt Nihei of LBNL is the project leader for this $1.67 million California Energy Commission funded program.

Seismic Monitoring Advisory Committee Meeting

Additional Seismic Monitoring and Research

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

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



Blue Labeled Points
Power Plant Locations

Yellow Labeled Points
Idealized 5 km x 5 km Sensor Installation Grid
ST001 – ST100

Red Labeled Points
Locations for 7 "Generation One" and 10 "Generation Two" Test Seismic Sensor Installations.

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 conducted with the project scientists.

Calpine Corporation 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.

The field testing and data analysis resulted in the following conclusions

- Seismic sensor housings were modified due to issues with water penetration.
- Seismic sensor mountings within the housing were modified to eliminate a 40 Hz resonant frequency degrading the data quality.
- Data quality from co-located sensors then determined to be is consistent with the permanent LBNL stations.
- The solar panel design was improved, power consumption minimized, and two ports for SDHC* data cards included.
- The instruments should be cemented directly to rock outcrops for best sensor coupling (and with no excavation permit required).
- A suitable rock outcrop nearly always available within a reasonable distance of the idealized grid location.

Generation Three Sensor Station

Sensor Installation on Rock Outcrop

* Secure Digital High Capacity

Seismic Monitoring Advisory Committee Meeting

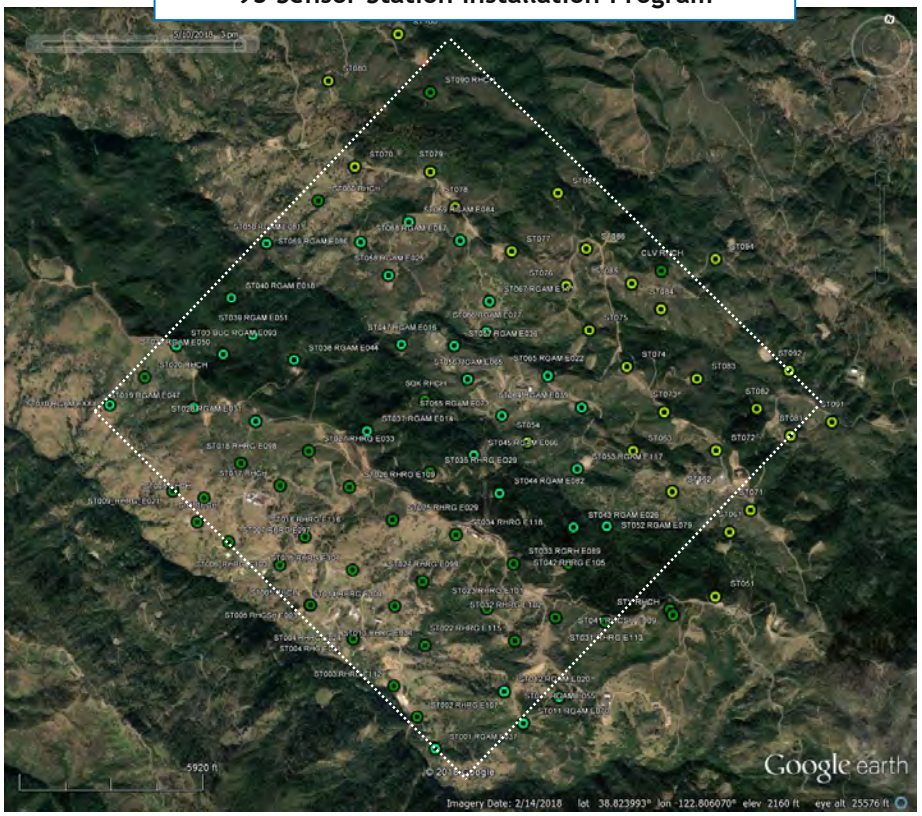
Additional Seismic Monitoring and Research

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

A total of 93 three component seismic sensor stations have been installed as of 10 May 2018, with much effort by project scientists Ramsey Haught (LBNL), Dr. Roland Gritto (AIT), Alex Morales (LBNL), Ed Nichols (LBNL) and John Peterson (LBNL. The actual station locations are as close as possible to the idealized sensor grid locations, with limitation imposed by the extreme topography, dense vegetation, and the need for firm surface conditions with good sun exposure.

Yellow Labeled Points
Idealized **Installation Locations for**
100 Sensor Station Installation Grid

Green Labeled Points
Actual **Installation Locations for**
93 Sensor Station Installation Program



Seismic Research Collaboration with Seismic Warning Systems

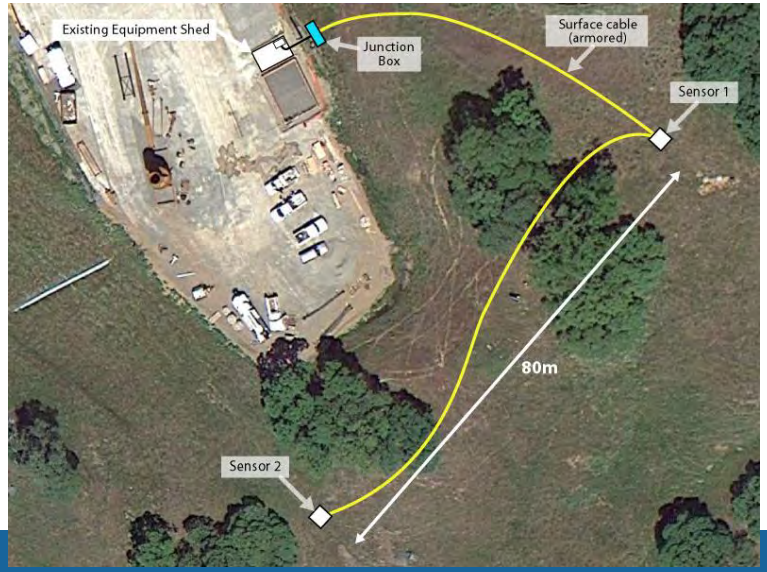
Early Detection and Warning System for Natural Earthquakes

SEISMIC WARNING SYSTEMS

Primary Goal

Automated control (and shutdown) of natural gas, electricity and water supply for refineries, chemical plants, public schools, medical facilities, …

Two test sensors at The Geysers Prati 32 well pad.
Installation date 15 September 2014.
Tied in to Calpine power and communications.



Geysers Project Goals

Refinement of event detection software to:

- Avoid false positives (caused by human activity)
- Distinguish between:
  - smaller seismic events typical of The Geysers these should be ignored
  - large seismic events (earthquakes) triggering automated warnings and shutdowns

Seismic Monitoring Advisory Committee Meeting
Research Collaborations

Calpine has greatly appreciated the experience and friendly guidance of Joe Austin; Division of Oil, Gas and Geothermal Resources concerning geological issues and seismicity analysis at The Geysers.

Lawrence Berkeley National Laboratory
- 36 station three-component permanent seismic monitoring network
- Collaboration on successful DOE co-funded EGS Demonstration Project, including two temporary seismic monitoring networks
- Collaboration on high-temperature tolerant borehole fiber optical seismic sensor testing
- Borehole seismic sensor installation and testing in the southeast Geysers
- Initiating collaboration for high-resolution imaging of fluid flow paths using a dense seismic network and automated processing

United States Geological Survey
- Geysers' seismicity processing and real-time availability, detailed analysis of magnitude ≥ 3.5 events
- Collaboration on full-waveform six-component (3 translational/3 rotational) seismic sensor testing
- Collaboration on Silicon Audio high-sensitivity optical accelerometer testing

Massachusetts Institute of Technology
- Collaboration on installation and operation of three continuous monitoring GPS instruments

Array Information Technology
- Research Collaborations with European GEISER Project
- Installation and recovery of 32 continuous broadband seismic recording instruments from GFZ Potsdam / GEISER Instrument Pool

GFZ Potsdam
- Collaboration on studies of spatiotemporal induced seismicity changes associated with variable water injection in the northwest Geysers

United States Seismic Systems
- High-temperature tolerant borehole fiber optical seismic sensor array test program

Seismic Warning Systems
- Northwest Geysers test site for calibration of earthquake early warning systems

Zizmos
- Geothermal Visitor Center test site for cloud-connected seismic network earthquake early warning systems