Seismic Monitoring Advisory Committee Meeting

01 October 2022 to 31 March 2023 Reporting Period

Calpine Geothermal Visitor Center

Thursday 11 May 2023

Craig Hartline
Senior Geophysicist
Geysers Power Company, LLC

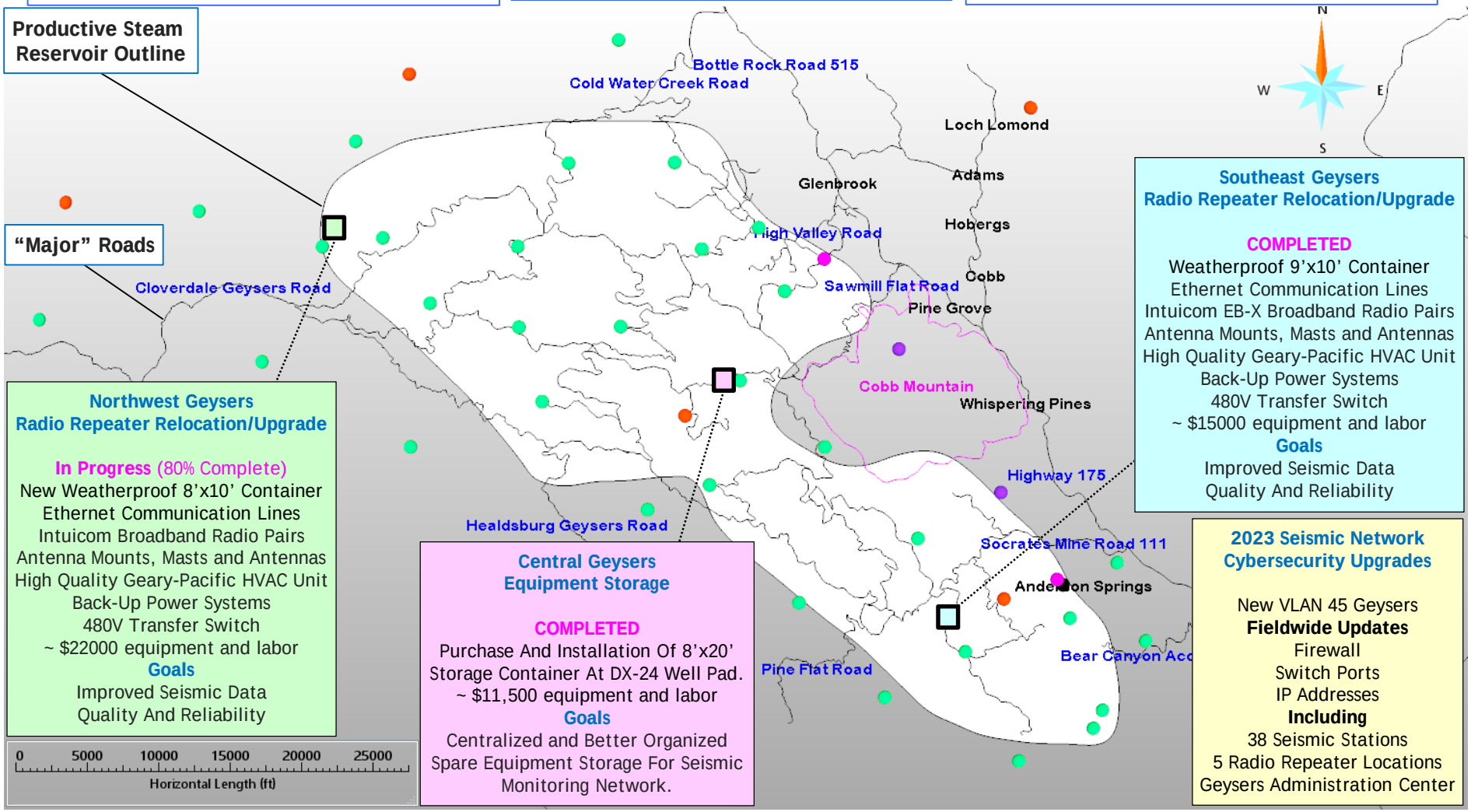
THE GEYSERS
GEYSERS POWER COMPANY, LLC
www.geysers.com

Geysers Geothermal Field, Nearby Communities and Seismic Monitoring Networks

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

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

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



Northwest Geysers
Radio Repeater Relocation/Upgrade

In Progress (80% Complete)
New Weatherproof 8'x10' Container
Ethernet Communication Lines
Intuicom Broadband Radio Pairs
Antenna Mounts, Masts and Antennas
High Quality Geary-Pacific HVAC Unit
Back-Up Power Systems
480V Transfer Switch
~ $22000 equipment and labor
Goals
Improved Seismic Data
Quality And Reliability

Central Geysers
Equipment Storage

COMPLETED
Purchase And Installation Of 8'x20' Storage Container At DX-24 Well Pad.
~ $11,500 equipment and labor
Goals
Centralized and Better Organized Spare Equipment Storage For Seismic Monitoring Network.

Southeast Geysers
Radio Repeater Relocation/Upgrade

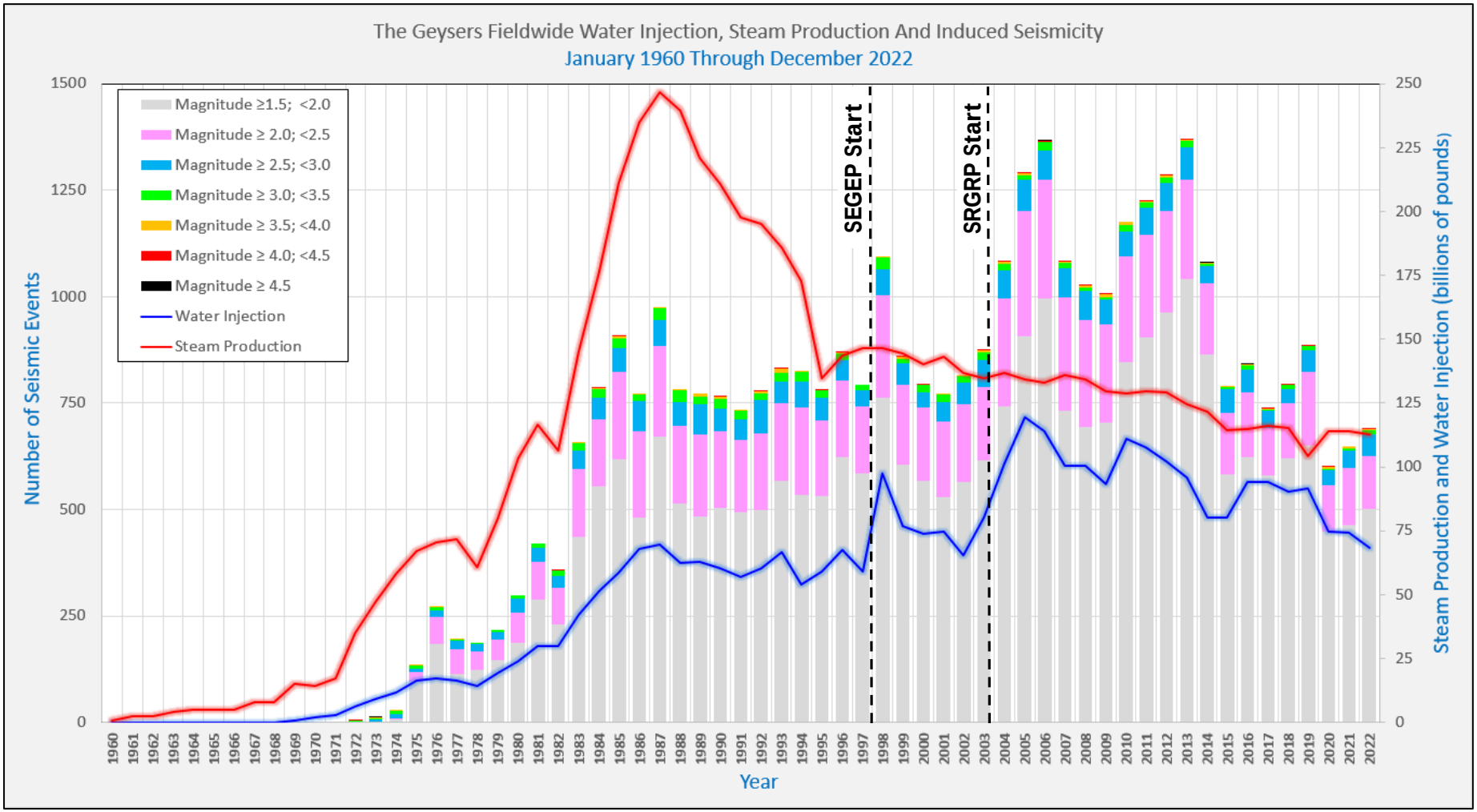
COMPLETED
Weatherproof 9'x10' Container
Ethernet Communication Lines
Intuicom EB-X Broadband Radio Pairs
Antenna Mounts, Masts and Antennas
High Quality Geary-Pacific HVAC Unit
Back-Up Power Systems
480V Transfer Switch
~ $15000 equipment and labor
Goals
Improved Seismic Data
Quality And Reliability

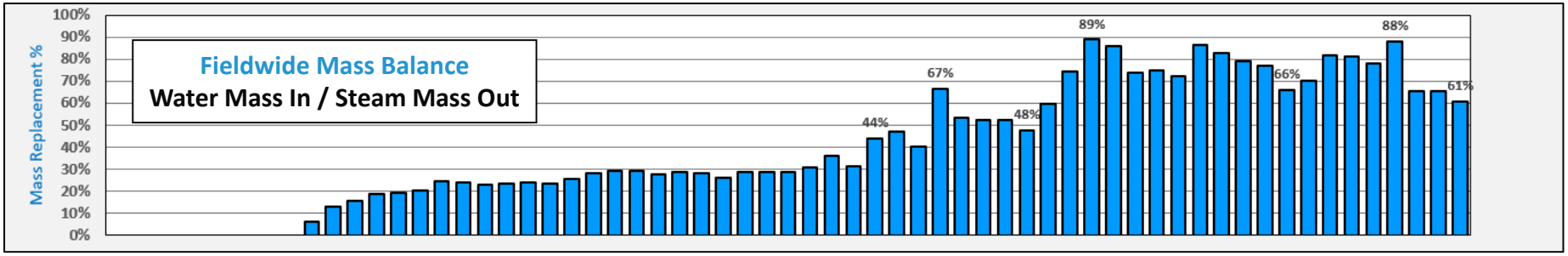
2023 Seismic Network
Cybersecurity Upgrades

New VLAN 45 Geysers
Fieldwide Updates
Firewall
Switch Ports
IP Addresses
Including
38 Seismic Stations
5 Radio Repeater Locations
Geysers Administration Center

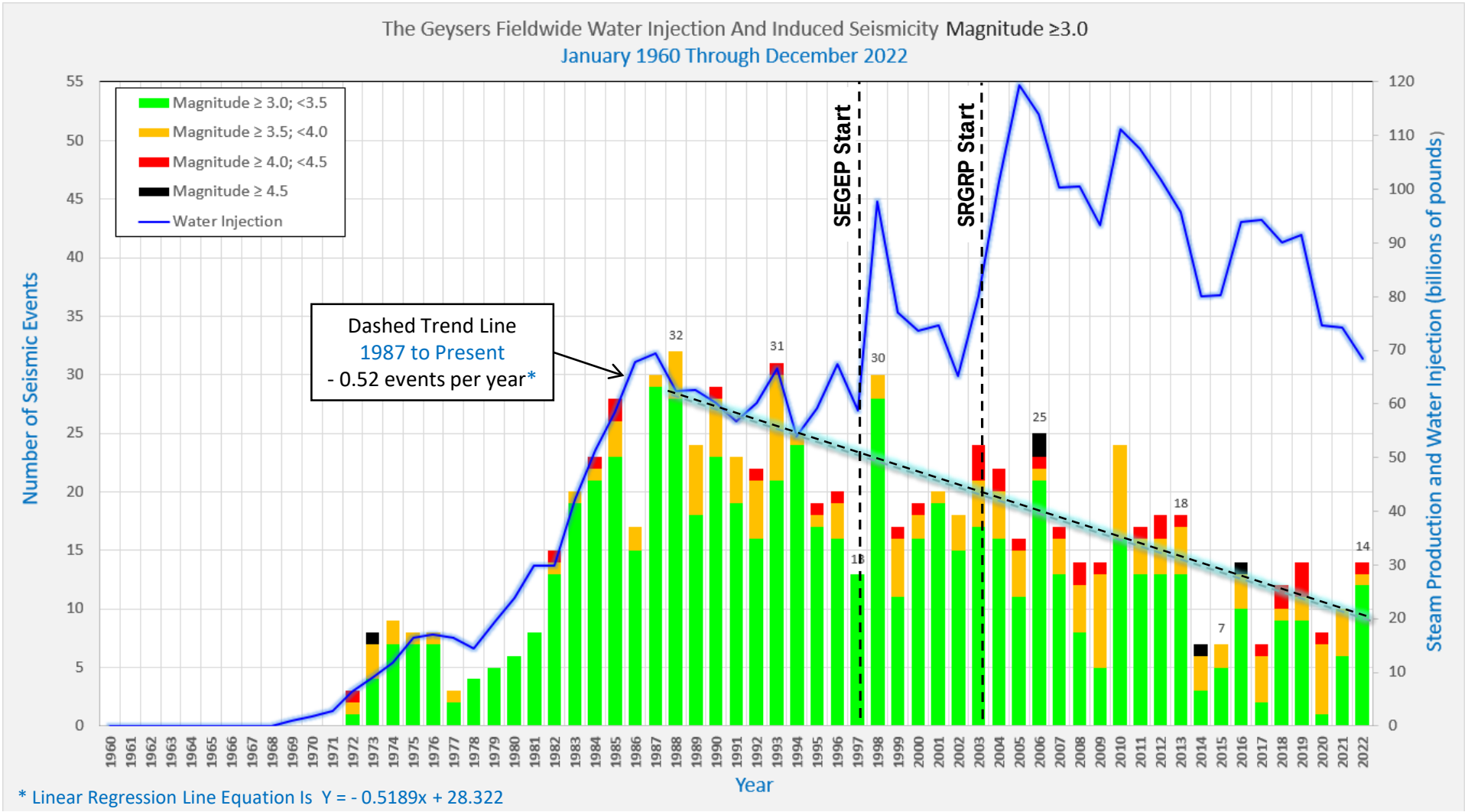
* The closely-spaced LBNL seismic monitoring stations allow accurate energy and hypocenter determination of Geysers' seismic events to *approximately* magnitude 0.8

Yearly Field-wide Steam Production, Water Injection and Seismicity

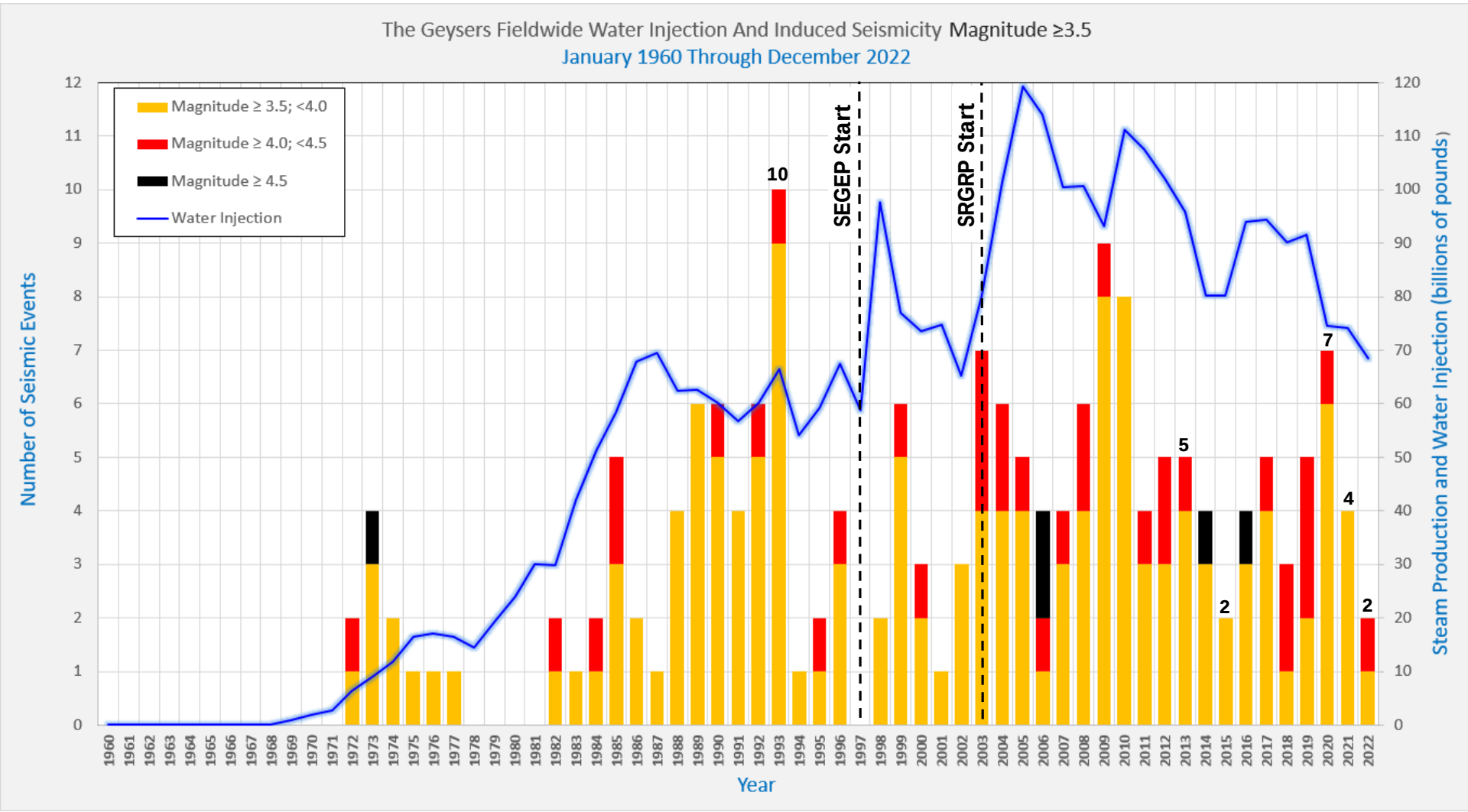




Yearly Field-wide Water Injection and All Seismicity Magnitude ≥3.0

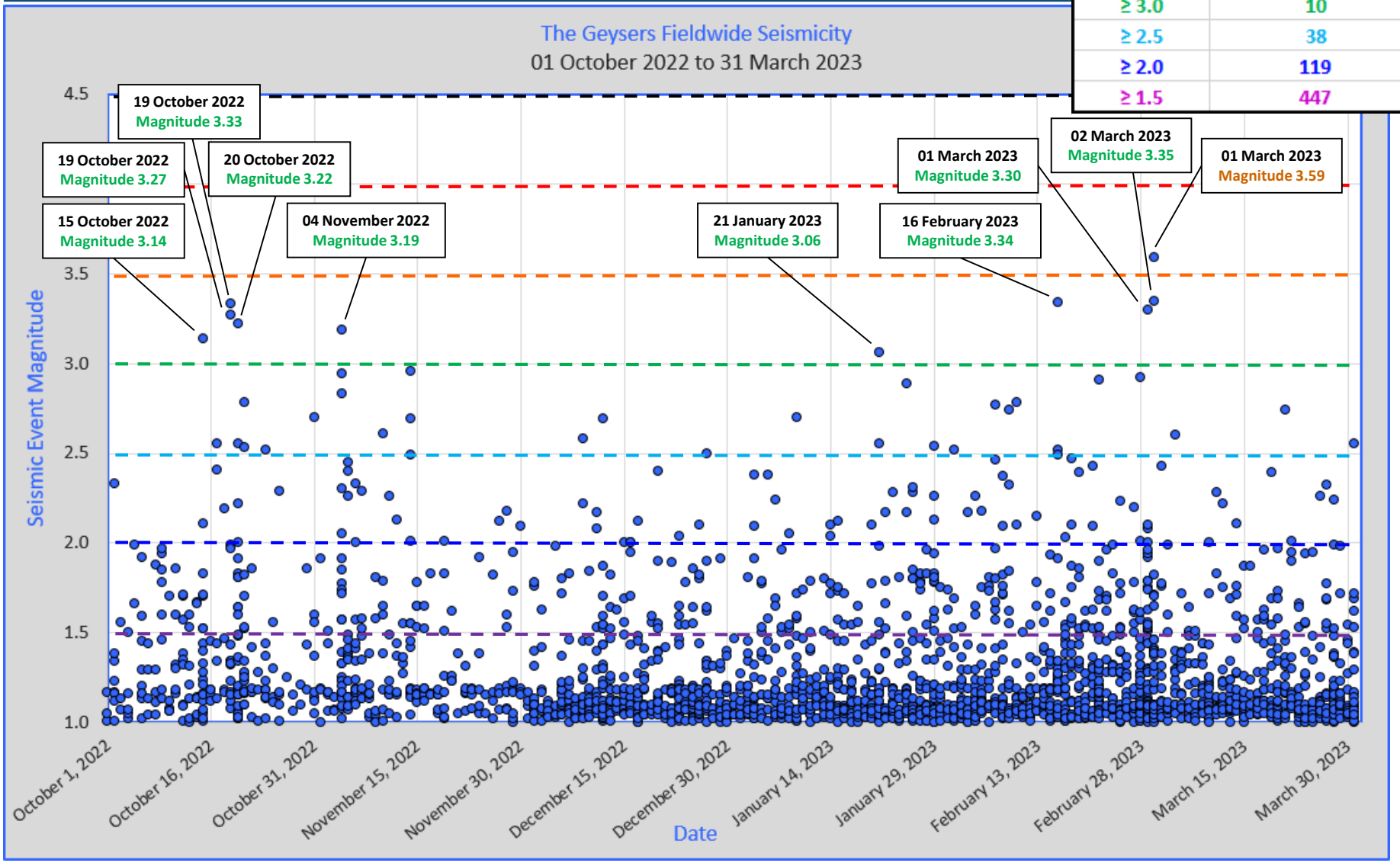


Yearly Field-wide Water Injection and All Seismicity Magnitude ≥3.5

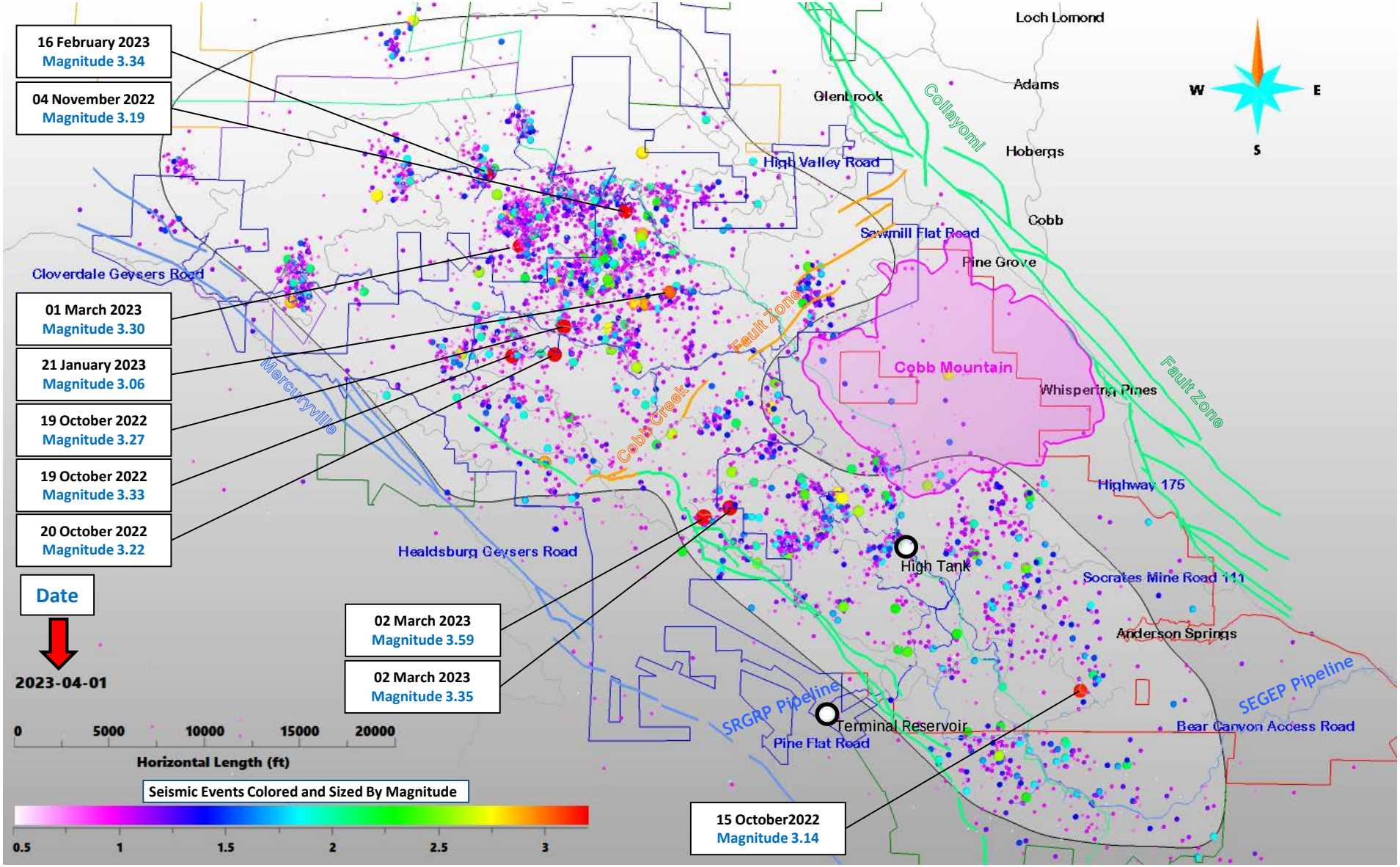


Field-wide Seismicity Analysis From 01 October 2022 to 31 March 2023

Magnitude	Number Of Events
≥ 4.5	0
≥ 4.0	0
≥ 3.5	1
≥ 3.0	10
≥ 2.5	38
≥ 2.0	119
≥ 1.5	447

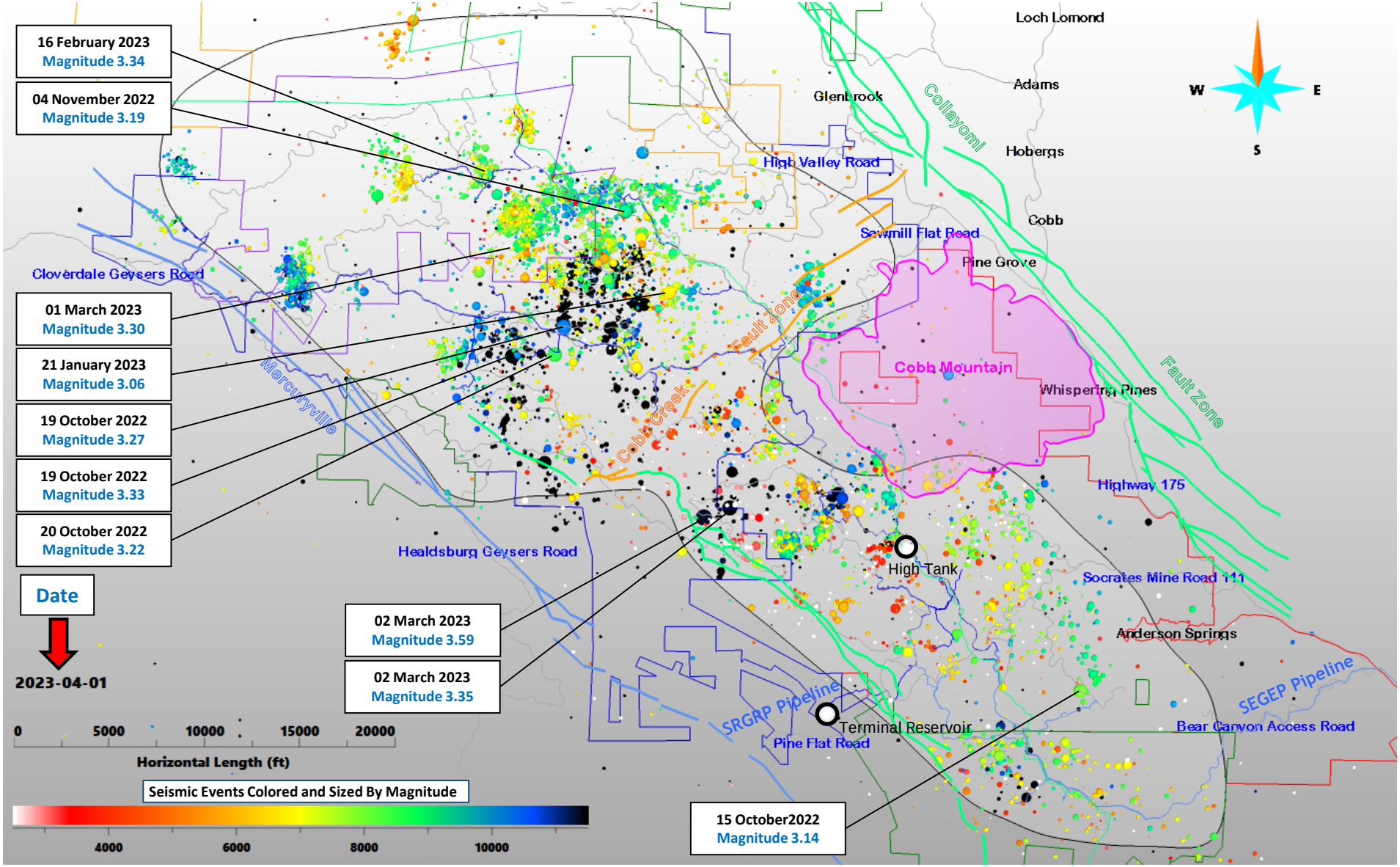


Field-wide Seismicity Animation At Two Week Interval – Color Scaled By Magnitude



Waveform data, metadata, or data products for this study were accessed through the Northern California Earthquake Data Center (NCEDC), doi:10.7932/NCEDC."

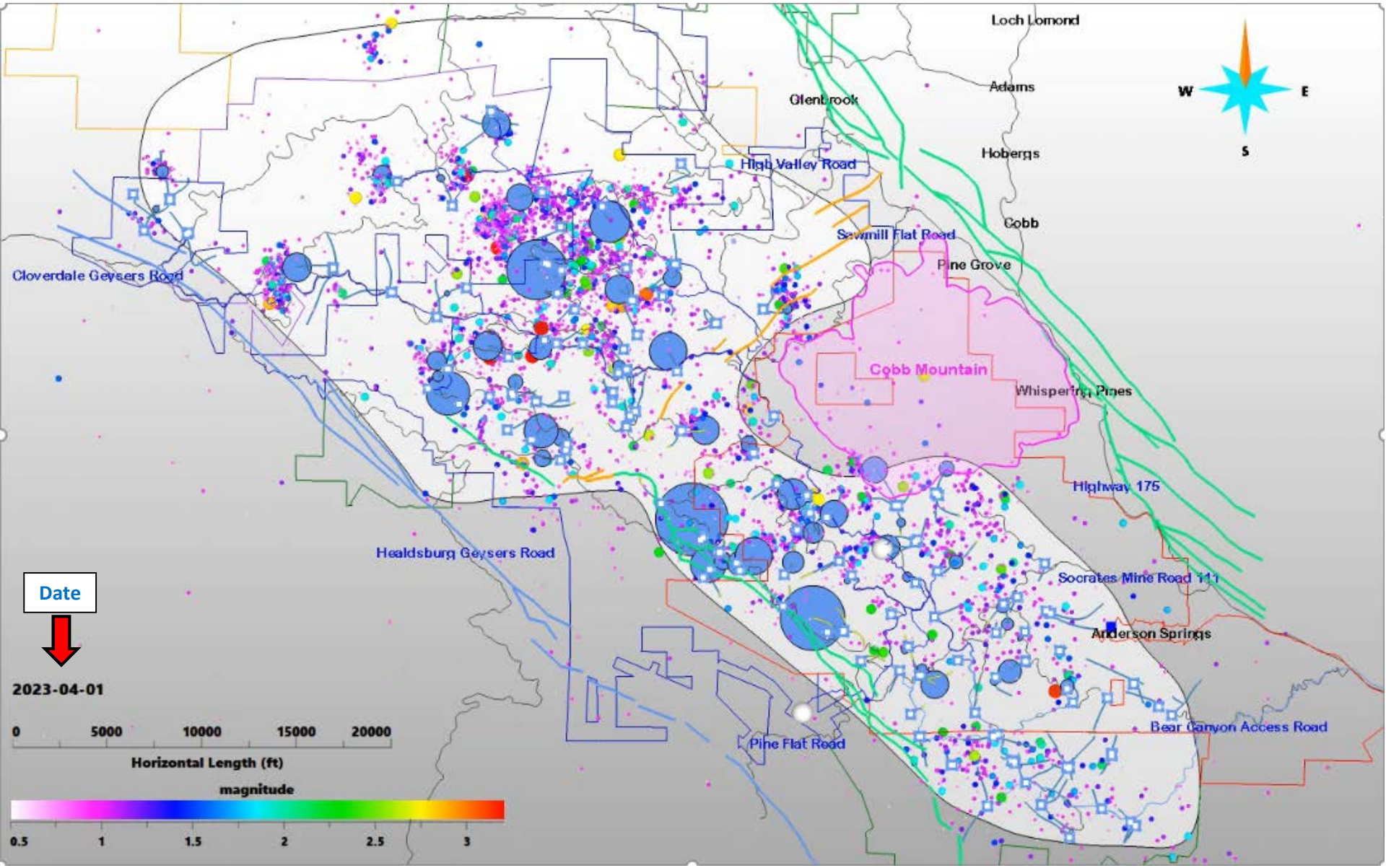
Field-wide Seismicity Animation At Two Week Interval – Color Scaled By Magnitude



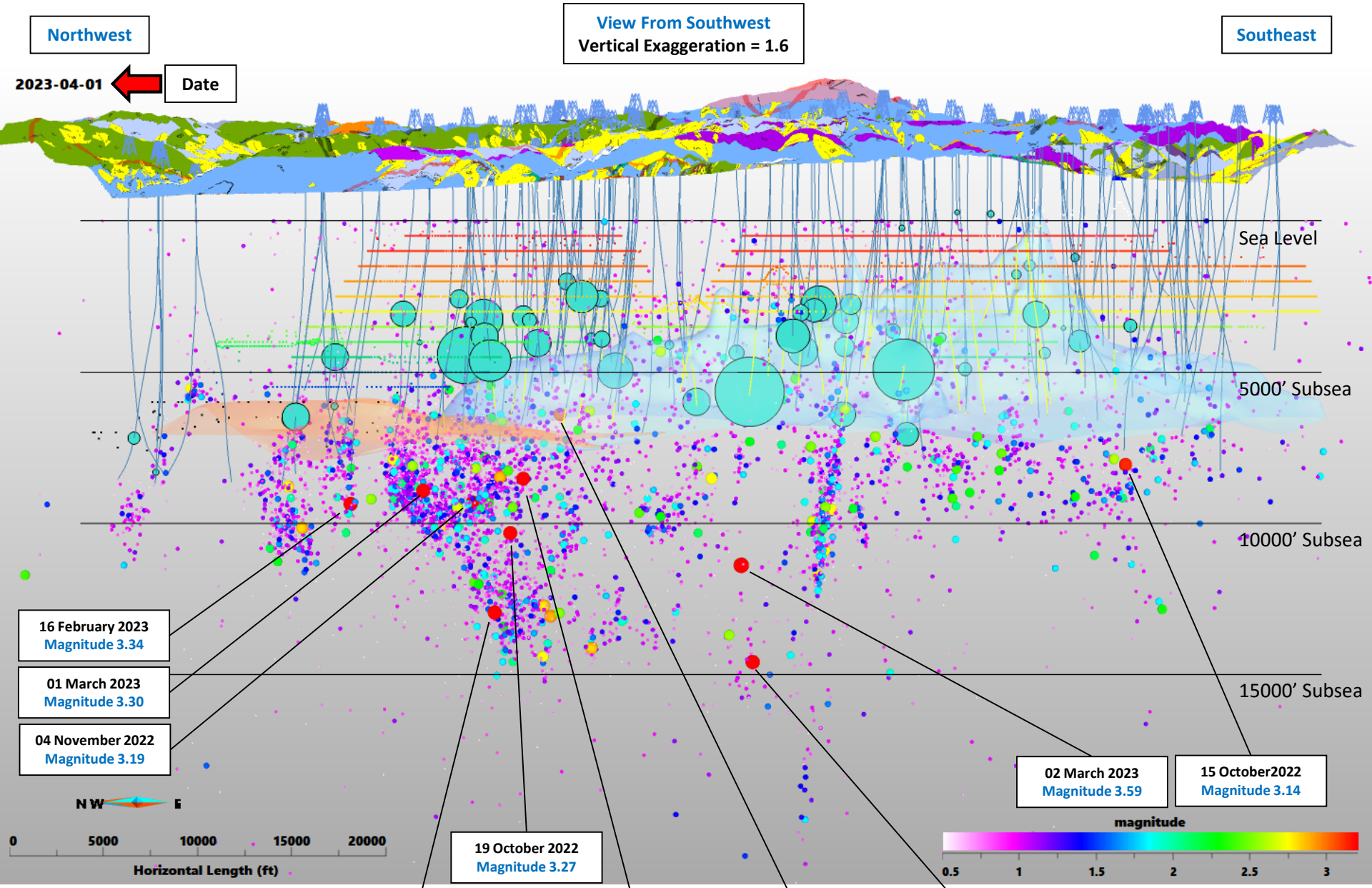
Waveform data, metadata, or data products for this study were accessed through the Northern California Earthquake Data Center (NCEDC), doi:10.7932/NCEDC."

IMAGE: Field-wide Water Injection and Induced Seismicity – Color Scaled By Magnitude

Blue Discs Proportional To Daily Injected Water Volume



VIDEO: Water Injection And Induced Seismicity Daily Animation From 01 October 2022 Through 31 March 2023



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

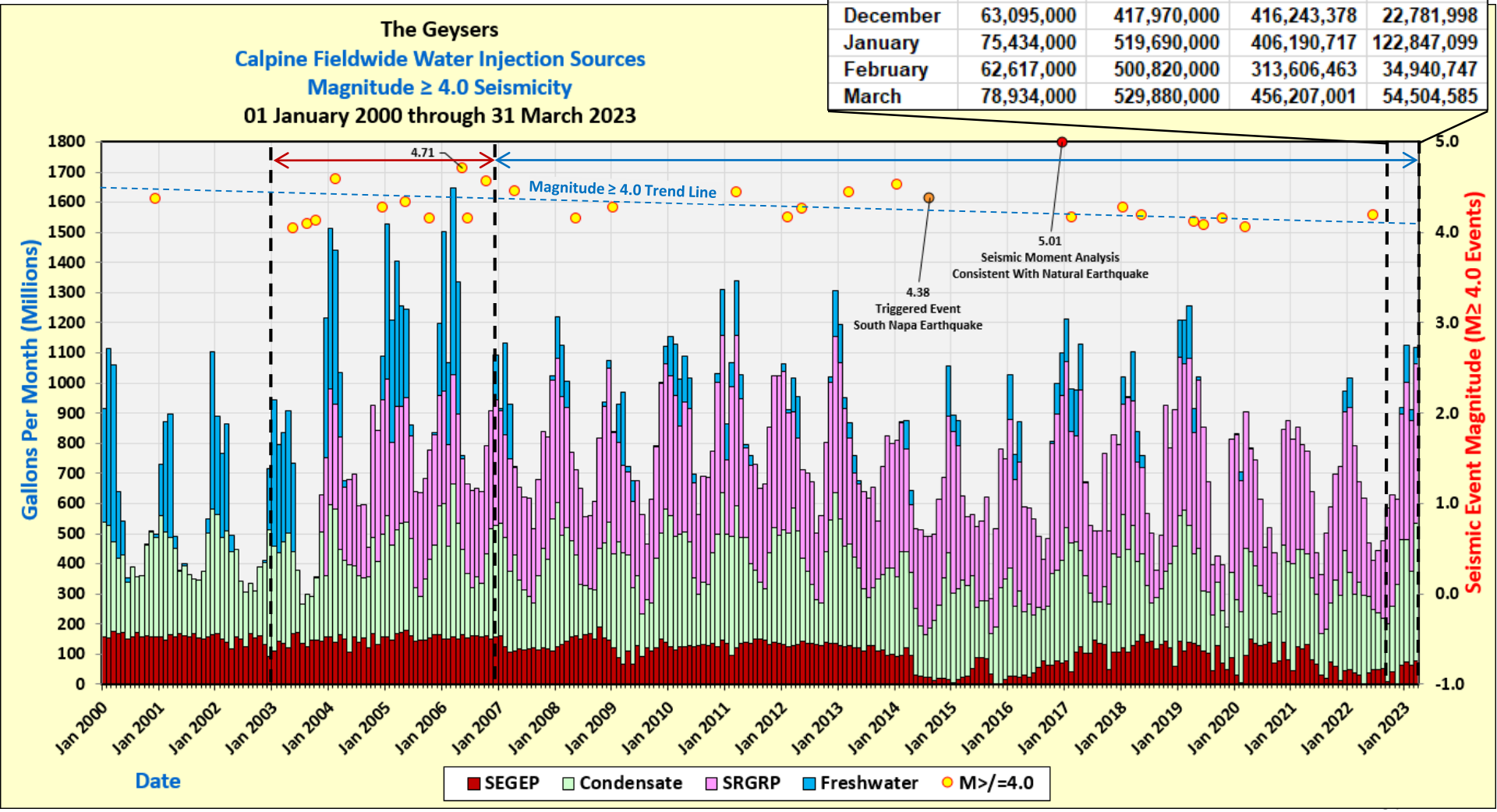
The Average Number of Magnitude ≥ 4.0 Events Since January 2007 is 1.11 Per Year

Time Period	Magnitude ≥ 4.0 Seismic Events
January 2003 through December 2006	2.50 per year
January 2007 through March 2023	1.11 per year

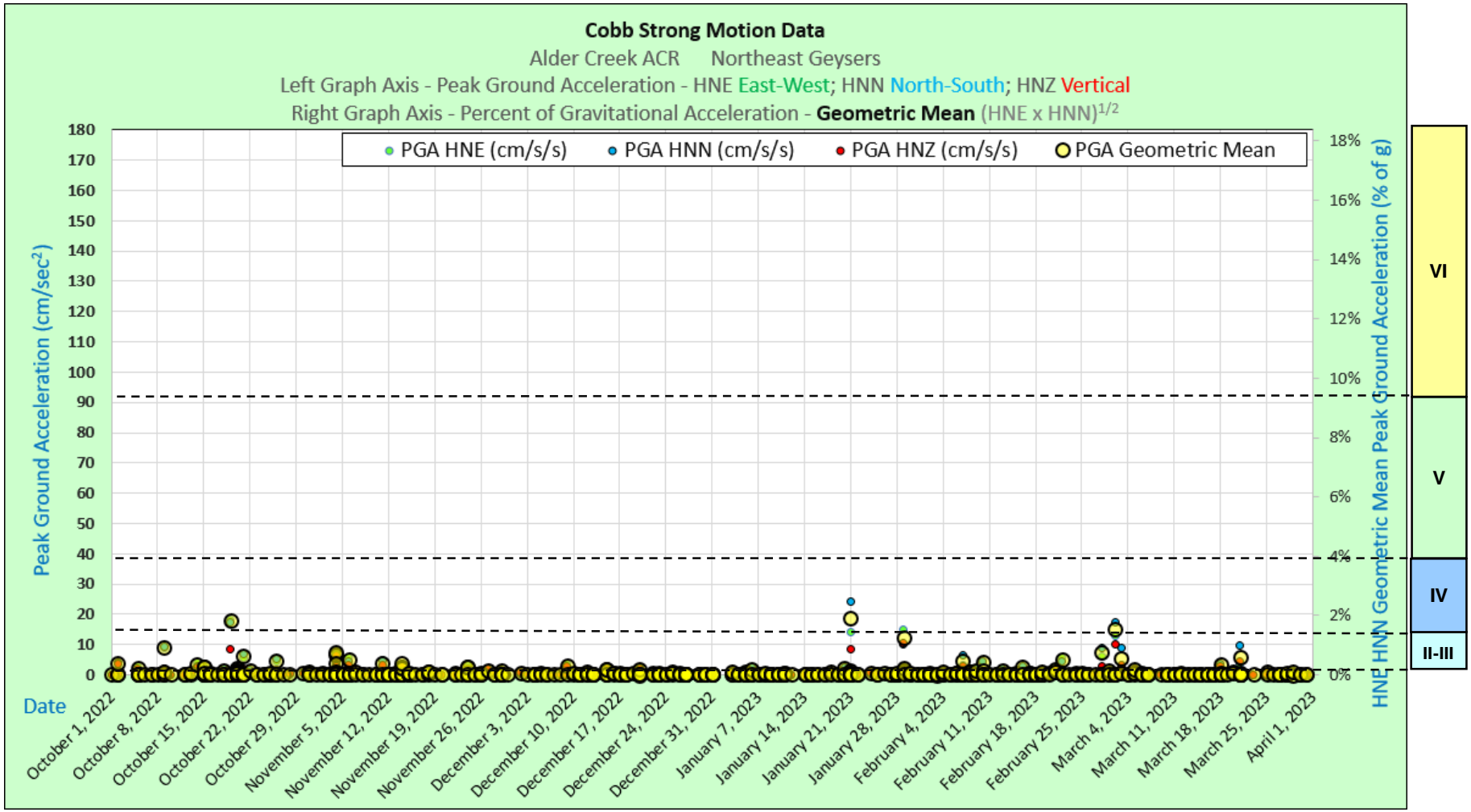
Water Supply for Six Month Reporting Period

Water Injection By Source (Gallons)

Month	SEGEP	SRGRP	Condensate	Fresh Water
October	41,600,000	370,540,000	218,365,670	0
November	2,832,000	281,470,000	330,340,848	0
December	63,095,000	417,970,000	416,243,378	22,781,998
January	75,434,000	519,690,000	406,190,717	122,847,099
February	62,617,000	500,820,000	313,606,463	34,940,747
March	78,934,000	529,880,000	456,207,001	54,504,585

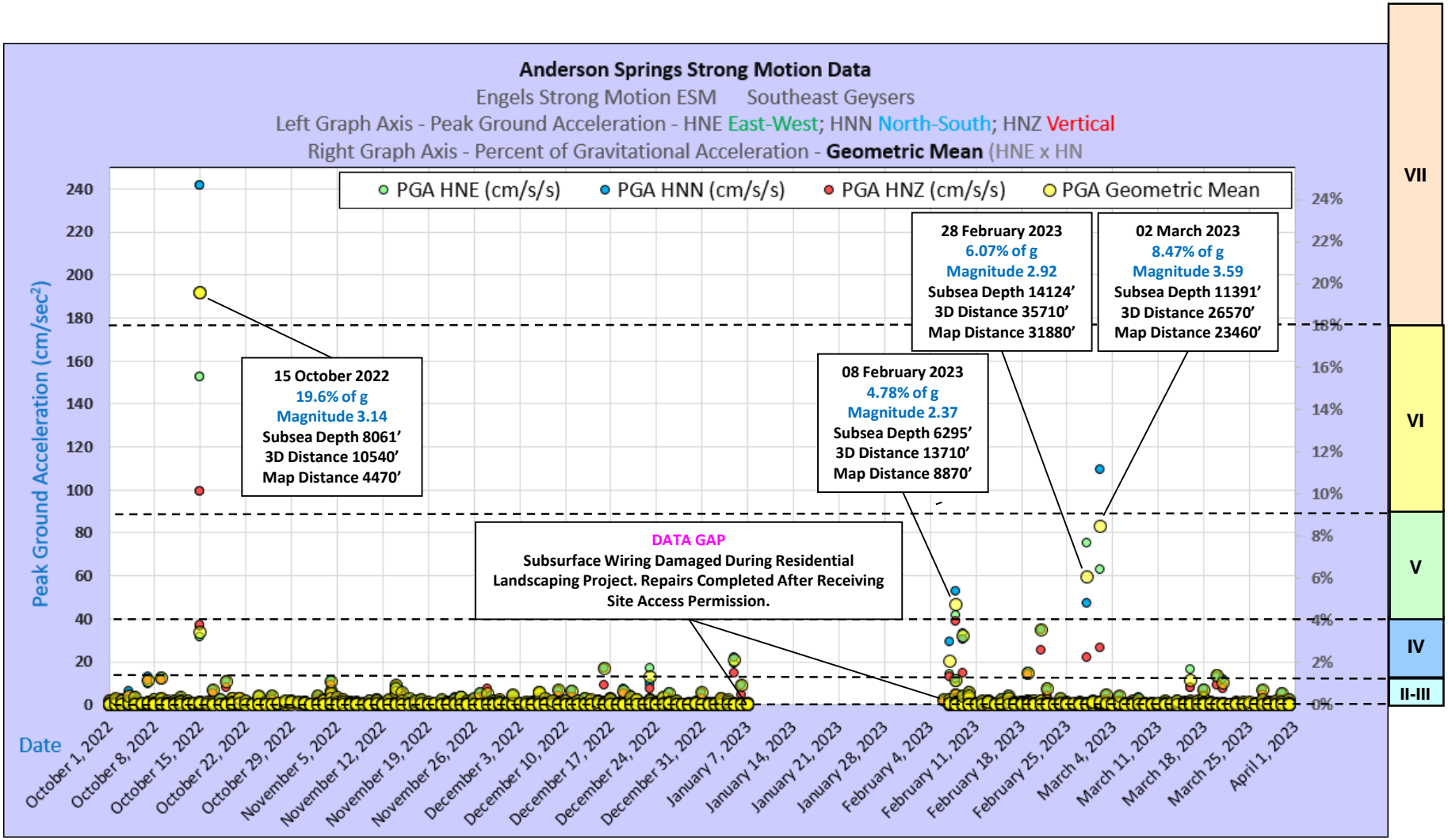


Cobb Area: Strong Motion Determinations At Alder Creek Strong Motion Station



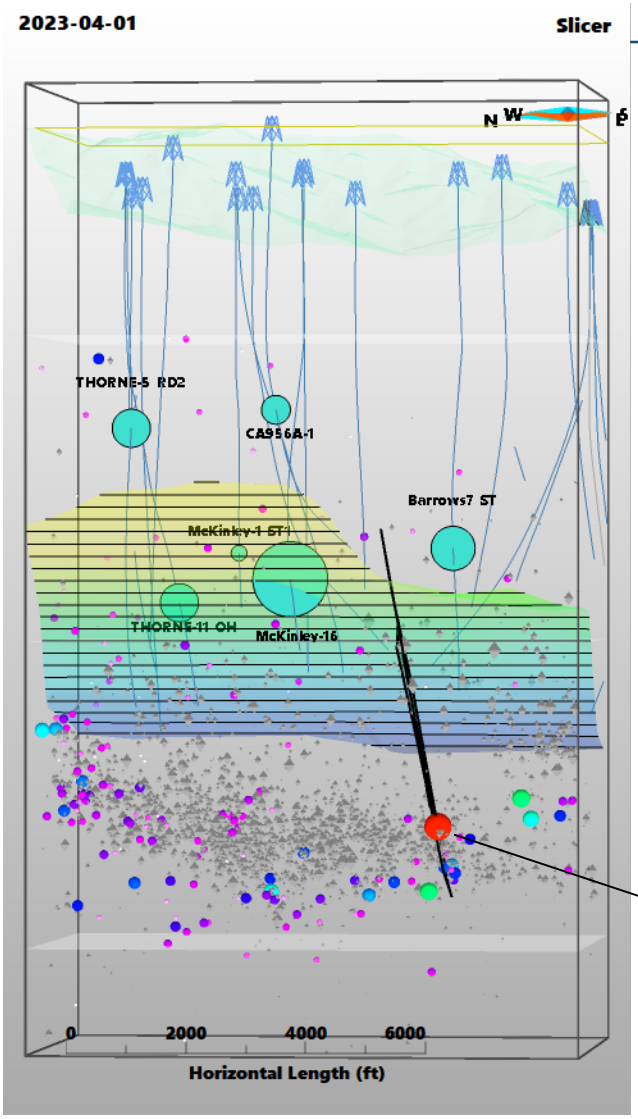
Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	None	None	None	Very Light	Light	Moderate	Mod/Heavy	Heavy	Very Heavy
Peak Acceleration (% of g)	< 0.17	0.17 - 1.4	1.4 - 3.9	3.9 - 9.2	9.2 - 18.0	18.0 - 34.0	34.0 - 65.0	65.0 - 124.0	> 124.0
Peak Velocity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

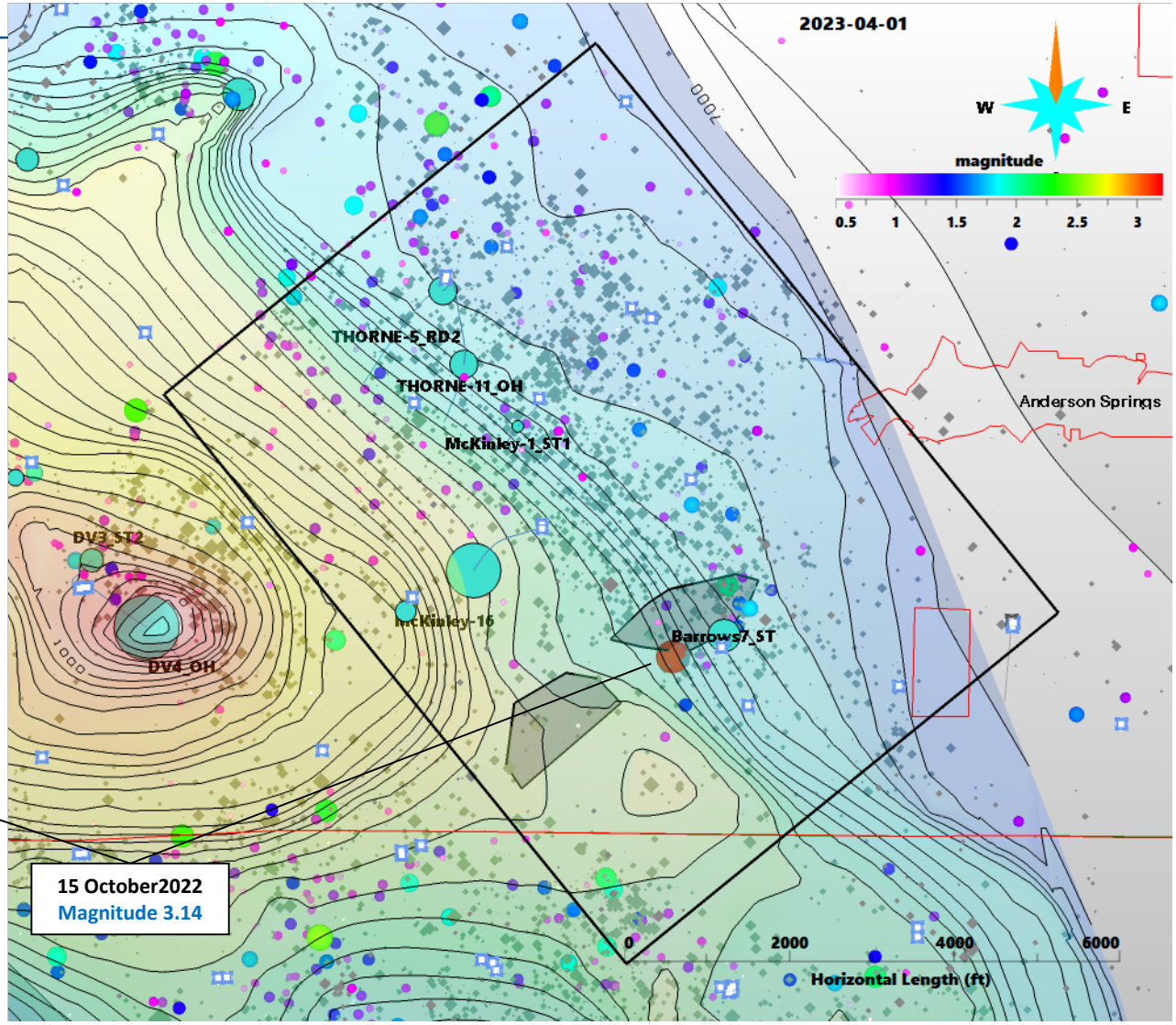
Anderson Springs Area: Strong Motion Determinations At Engels Strong Motion Station



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

Southeast Geysers 15 October 2022 Magnitude 3.14 Seismic Event





Earthquake Focal Mechanisms
SKUA GOCAD Macro Development

Macro Originally Created By Andreas Plesch; Harvard University

visualize focal mechanisms as beach balls v5ap ...

Visualize focal mechanisms as beach balls.

Requires Z positive upward in Project settings.

Points: Focal_Mechanism_19Oct2022_Mag_3p27

PointSet Structural Properties

Strike: IR Strike — is Dip Direction

Dip: IR Dip

Rake: IR Rake

Magnitude: IR Mag

Name: IR Name

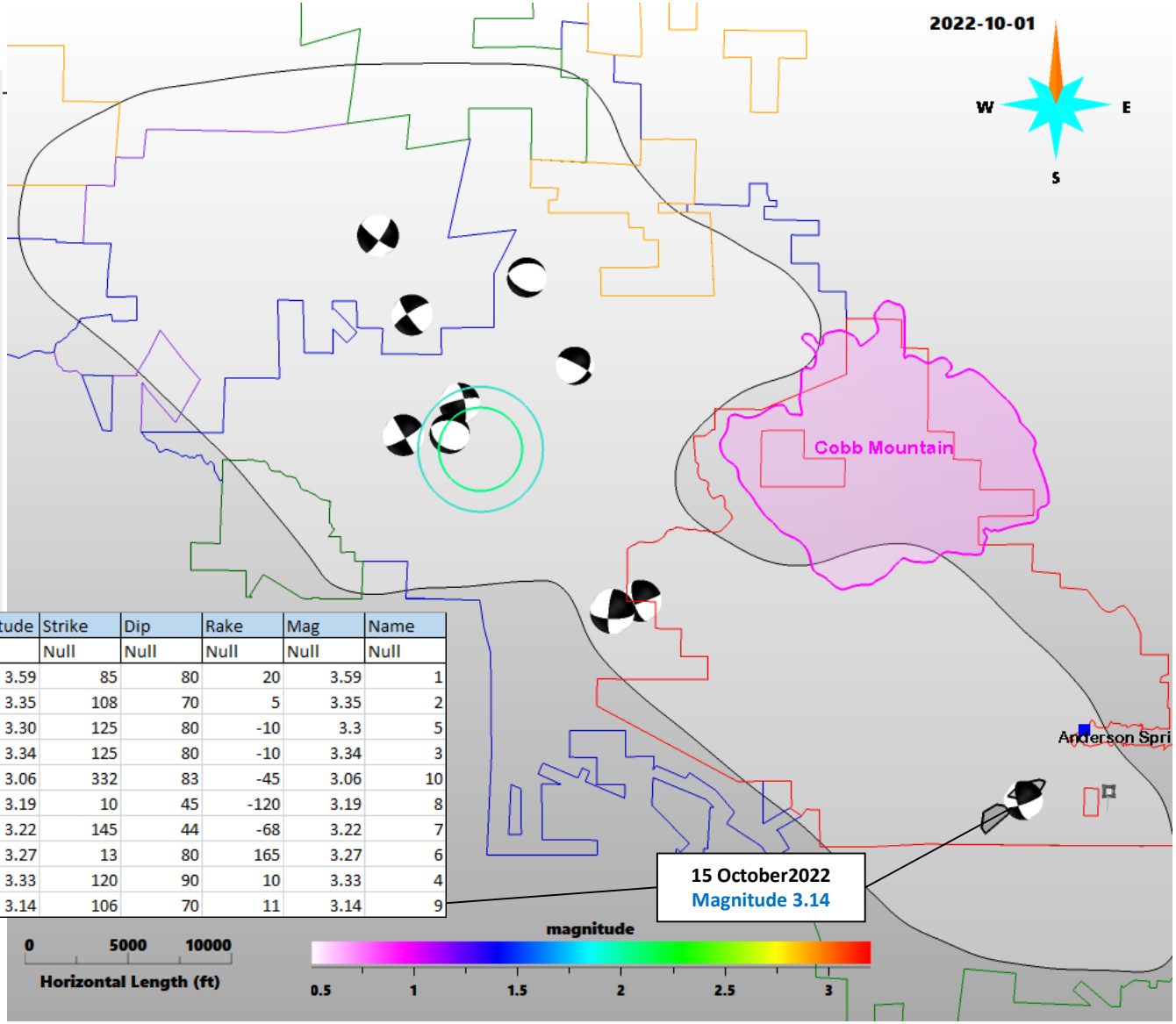
Advanced

Scaling Factor: 3

Resolution: 0

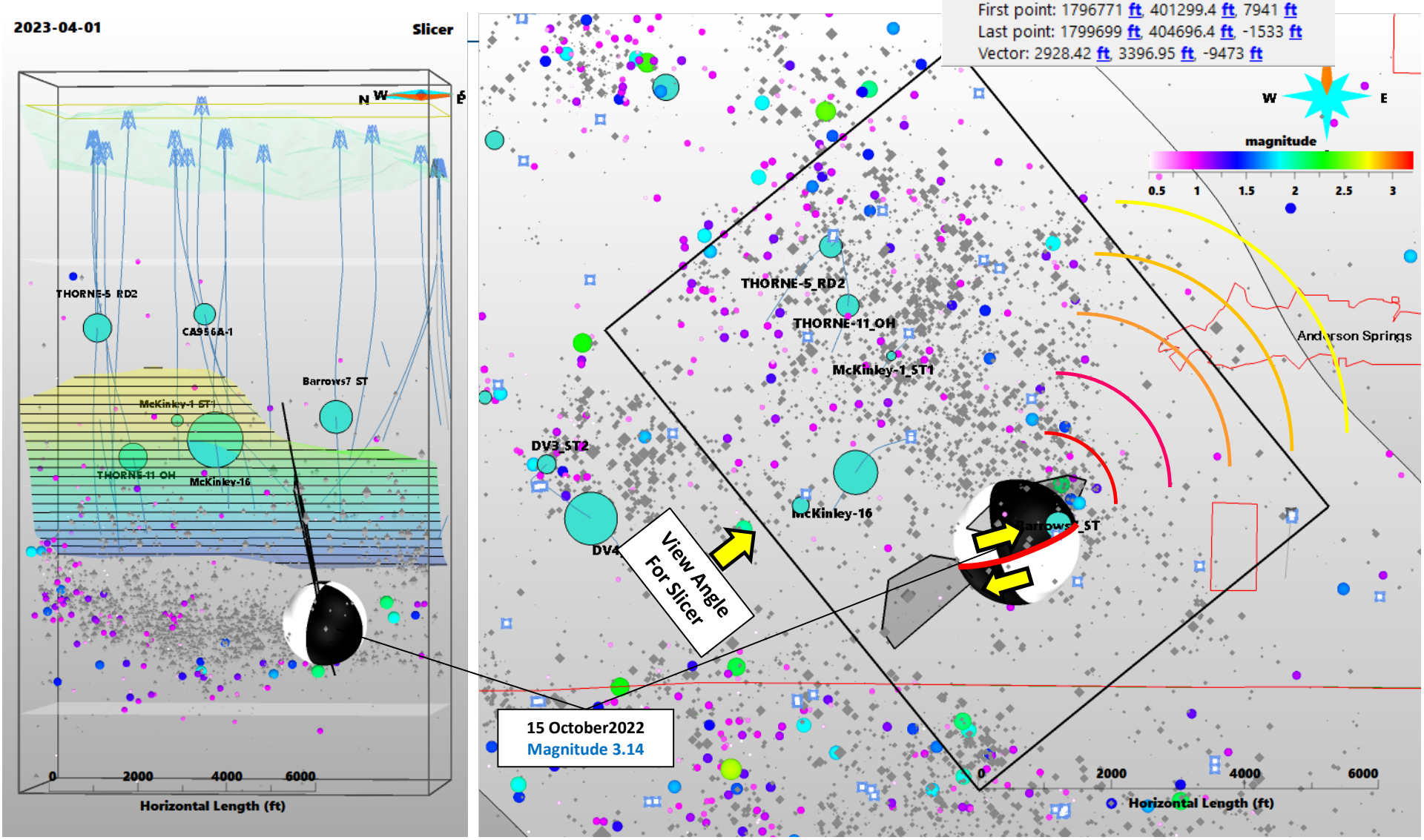
Enter a value between 0 (smooth) and 100 (rough).

DateTime	Easting	Northing	DepthFt	Magnitude	Strike	Dip	Rake	Mag	Name
YYYY:MM:DD:HH:MM:SS	ft	ft	ft	Null	Null	Null	Null	Null	Null
2023:03:02:21:16:50	1777040	410382	11391	3.59	85	80	20	3.59	1
2023:03:02:21:16:17	1778403	410887	14593	3.35	108	70	5	3.35	2
2023:03:01:07:09:40	1767425	424608	8921	3.30	125	80	-10	3.3	5
2023:02:16:19:13:53	1765793	428421	9363	3.34	125	80	-10	3.34	3
2023:01:21:03:27:50	1775238	422168	6404	3.06	332	83	-45	3.06	10
2022:11:04:20:26:33	1772927	426406	9311	3.19	10	45	-120	3.19	8
2022:10:20:00:02:34	1769229	418918	8524	3.22	145	44	-68	3.22	7
2022:10:19:23:59:50	1769709	420363	10325	3.27	13	80	165	3.27	6
2022:10:19:23:59:04	1767017	418839	12953	3.33	120	90	10	3.33	4
2022:10:15:17:30:41	1796770	401308	8061	3.14	106	70	11	3.14	9



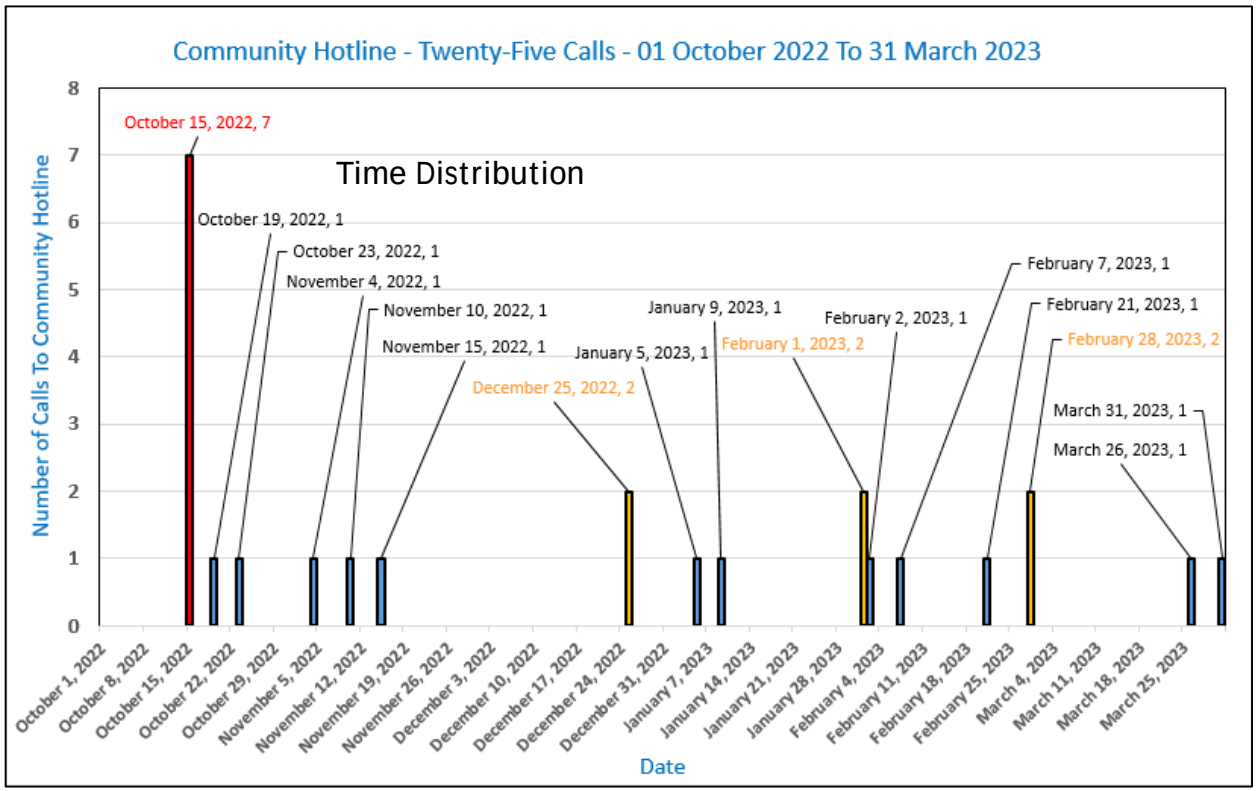
Waveform data, metadata, or data products for this study were accessed through the Northern California Earthquake Data Center (NCEDC), doi:10.7932/NCEDC."

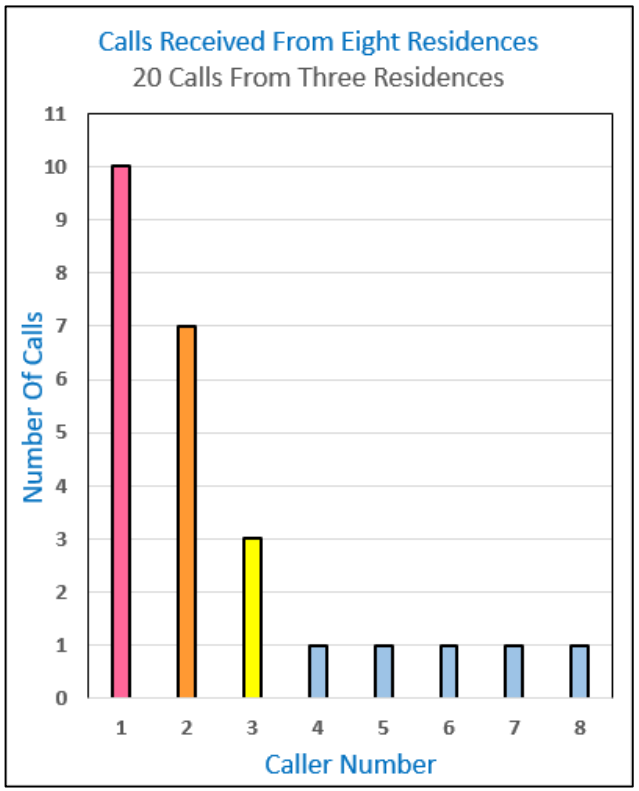
Southeast Geysers 15 October 2022 Magnitude 3.14 Seismic Event
Focal Mechanisms And Energy Transfer



Community Hotline
25 Calls

Anderson Springs 25 Calls
Cobb 0 Calls





Seismicity Mitigation

Individual Well Criteria For Minimization Of Water Well Volume/Rate Variability

Calpine IC&E Technicians have been testing the automation of injection well rate determinations with the following goals:
(1) accomplish effective level control with small flow modifications to multiple injection wells instead of large flow modifications to few wells
(2) allow temporary water surpluses and deficits fieldwide to be balanced without the need to make large modifications to injection well flows

This water well management goal is perfectly aligned with Calpine seismicity mitigation efforts.

Currently developing seismic mitigation criteria to assist with minimization of individual water well volume/rate variability.

Average Water Injection Rate
- Measured Values

Variability Of Water Injection Rate
- Median Absolute Deviation
- Average Distance Of Data Values From Median

Distance From Other Water Injection Wells
- Measured Centers Of Injection Separation

Distance From Communities
- Anderson Springs and Cobb Most Sensitive Communities
- Scalar Applied To Anderson Springs Due To Known Site Amplification Issues

Distance From Known Faults Of Significant Area
- Based On Interpretation Of Seismicity Patterns / Alignments

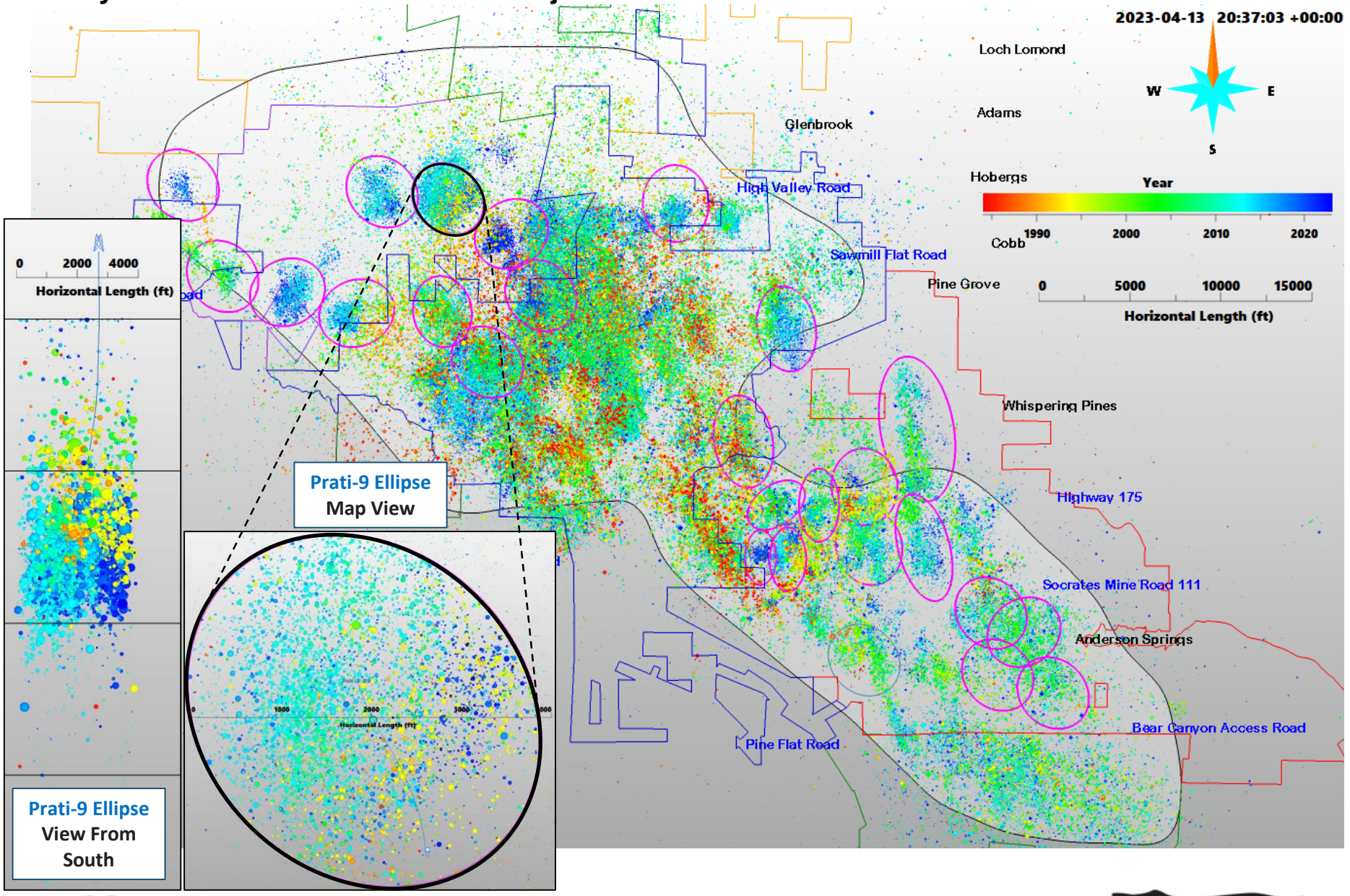
Largest Seismic Event(s) Within Well Ellipse
- Number of Events ≥ 2.65

Energy Release Within Well Ellipse
- Log10 (energy) = 11.8 + 1.5(magnitude)

B-Values (Magnitude vs. Frequency) Within Ellipse
- B-Values Based On Gutenberg–Richter Relationship
- Spatial and Temporal Changes In B-Values

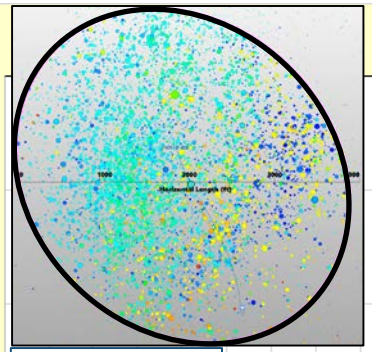
Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Area Of Influence for Individual Water Injection Wells Determined



Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Influence By Well Prati-9 RD In Northwest Geysers



Prati-9 Ellipse
Map View

Ellipse Prati-9 RD Induced Seismicity January 1984 to March 2023

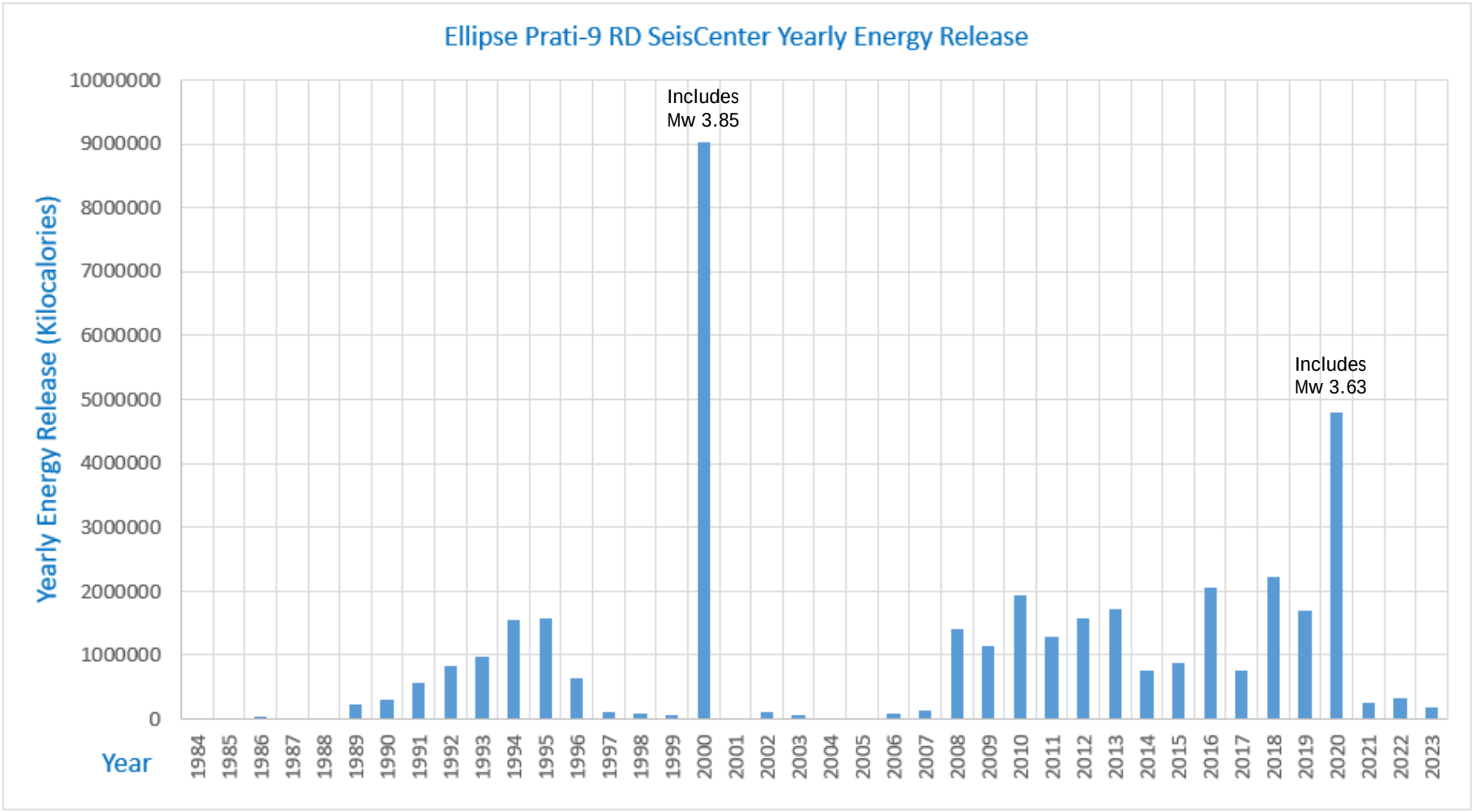
Seismic Event Magnitude

Date

3.85
3.02
3.16
3.63
3.35
3.18

Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

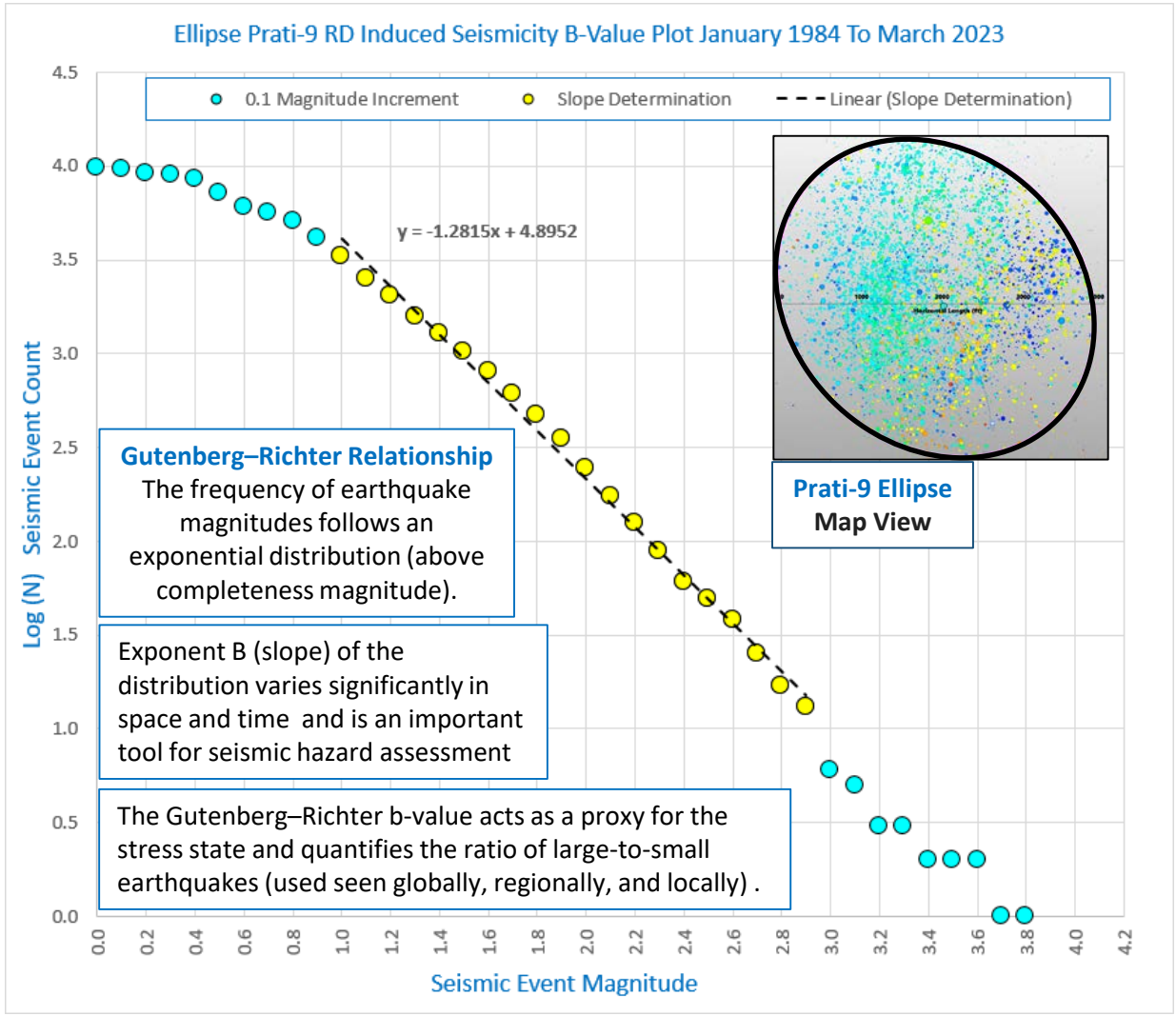
Primary Influence By Well Prati-9 RD In Northwest Geysers



Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Influence By Well Prati-9 RD

B-Values For Interval January 1984 To March 2023

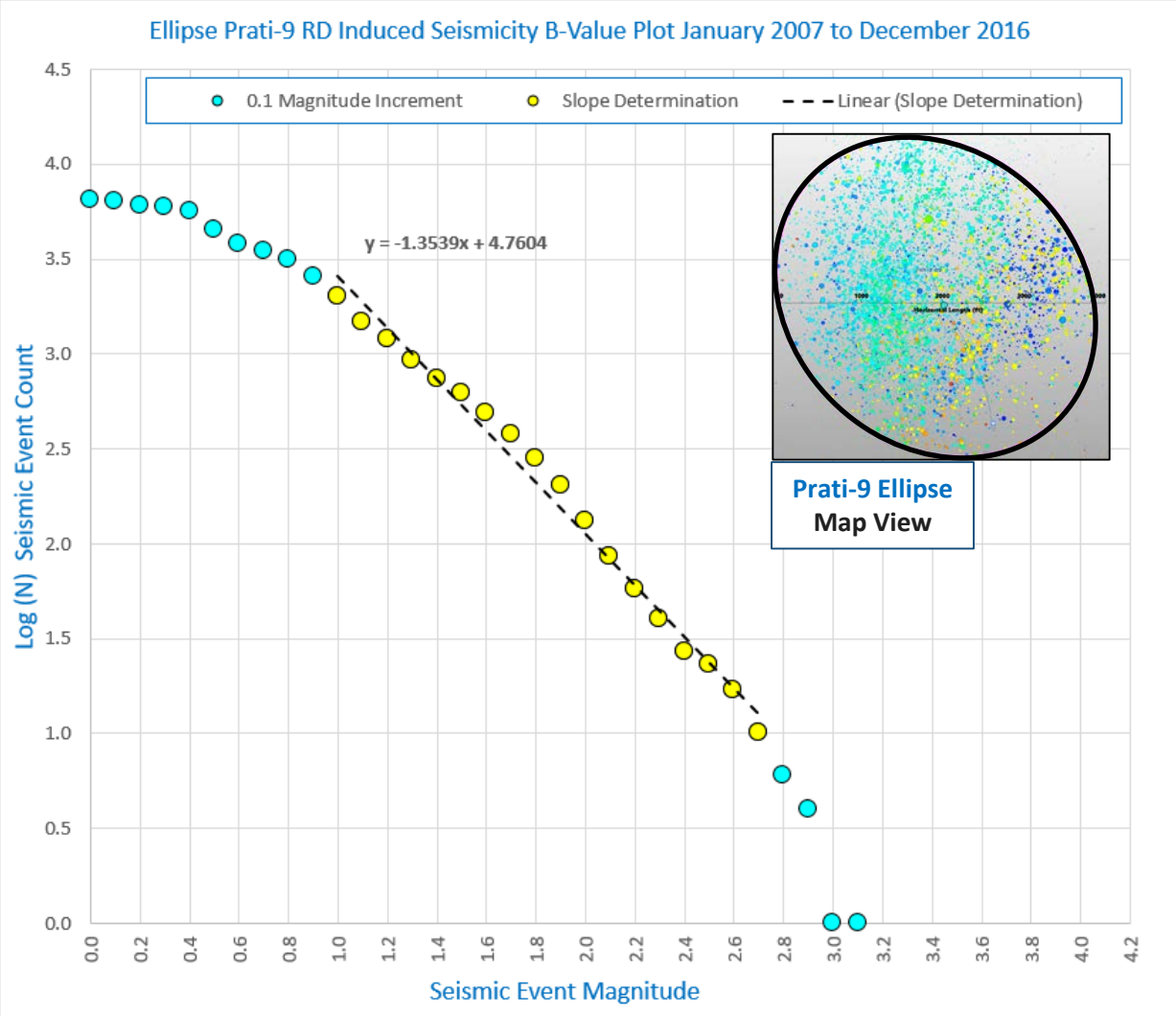


Minimum	>= Min	Log10
0.00	9859	3.99
0.10	9621	3.98
0.20	9187	3.96
0.30	9031	3.96
0.40	8466	3.93
0.50	7221	3.86
0.60	6068	3.78
0.70	5621	3.75
0.80	5115	3.71
0.90	4120	3.61
1.00	3282	3.52
1.10	2495	3.40
1.20	2037	3.31
1.30	1581	3.20
1.40	1287	3.11
1.50	1031	3.01
1.60	799	2.90
1.70	613	2.79
1.80	474	2.68
1.90	350	2.54
2.00	243	2.39
2.10	174	2.24
2.20	125	2.10
2.30	89	1.95
2.40	61	1.79
2.50	49	1.69
2.60	38	1.58
2.70	25	1.40
2.80	17	1.23
2.90	13	1.11
3.00	6	0.78
3.10	5	0.70
3.20	3	0.48
3.30	3	0.48
3.40	2	0.30
3.50	2	0.30
3.60	2	0.30
3.70	1	0.00
3.80	1	0.00

Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Influence By Well Prati-9 RD

B-Values For Interval January 2007 To December 2016

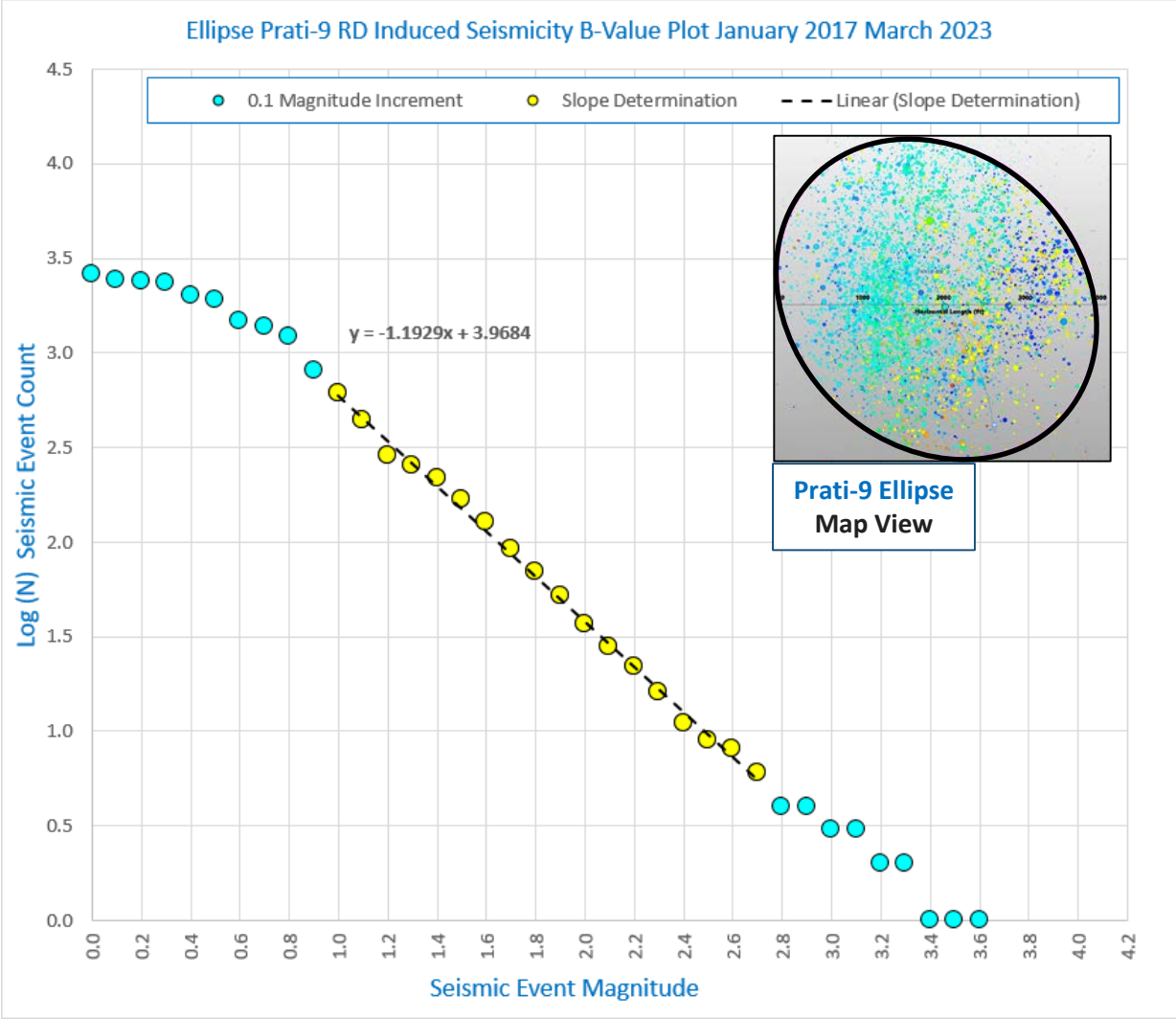


Minimum	>= Min	Log10
0.00	6464	3.81
0.10	6380	3.80
0.20	5989	3.78
0.30	5884	3.77
0.40	5656	3.75
0.50	4522	3.66
0.60	3808	3.58
0.70	3474	3.54
0.80	3114	3.49
0.90	2545	3.41
1.00	1989	3.30
1.10	1456	3.16
1.20	1202	3.08
1.30	921	2.96
1.40	736	2.87
1.50	618	2.79
1.60	485	2.69
1.70	375	2.57
1.80	280	2.45
1.90	202	2.31
2.00	131	2.12
2.10	85	1.93
2.20	57	1.76
2.30	40	1.60
2.40	27	1.43
2.50	23	1.36
2.60	17	1.23
2.70	10	1.00
2.80	6	0.78
2.90	4	0.60
3.00	1	0.00
3.10	1	0.00

Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Influence By Well Prati-9 RD

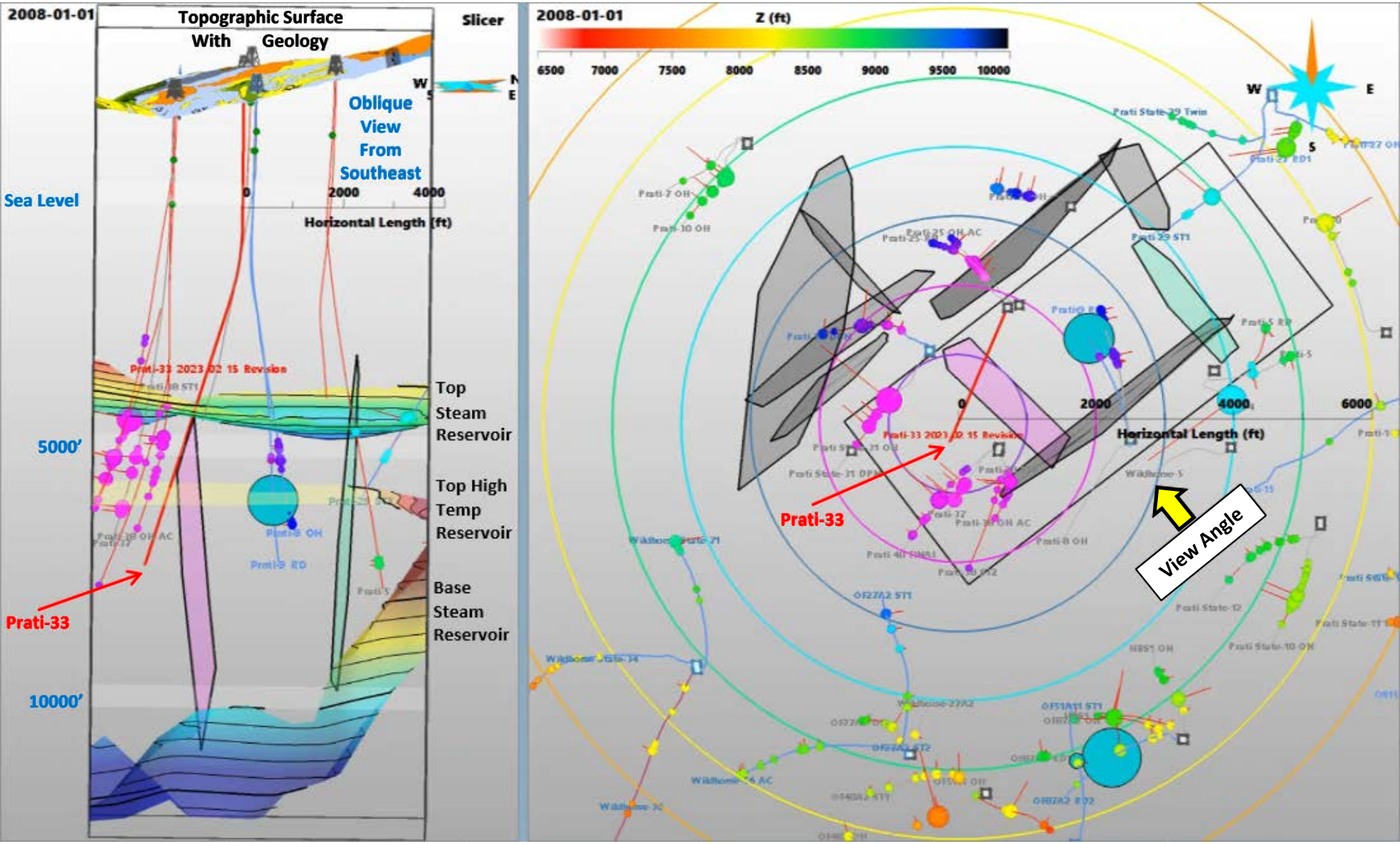
B-Values For Interval January 2017 To March 2023



Minimum	>= Min	Log10
0.00	2587	3.41
0.10	2435	3.39
0.20	2394	3.38
0.30	2345	3.37
0.40	2012	3.30
0.50	1904	3.28
0.60	1472	3.17
0.70	1366	3.14
0.80	1225	3.09
0.90	809	2.91
1.00	612	2.79
1.10	437	2.64
1.20	284	2.45
1.30	251	2.40
1.40	215	2.33
1.50	168	2.23
1.60	128	2.11
1.70	92	1.96
1.80	70	1.85
1.90	52	1.72
2.00	37	1.57
2.10	28	1.45
2.20	22	1.34
2.30	16	1.20
2.40	11	1.04
2.50	9	0.95
2.60	8	0.90
2.70	6	0.78
2.80	4	0.60
2.90	4	0.60
3.00	3	0.48
3.10	3	0.48
3.20	2	0.30
3.30	2	0.30
3.40	1	0.00
3.50	1	0.00
3.60	1	0.00

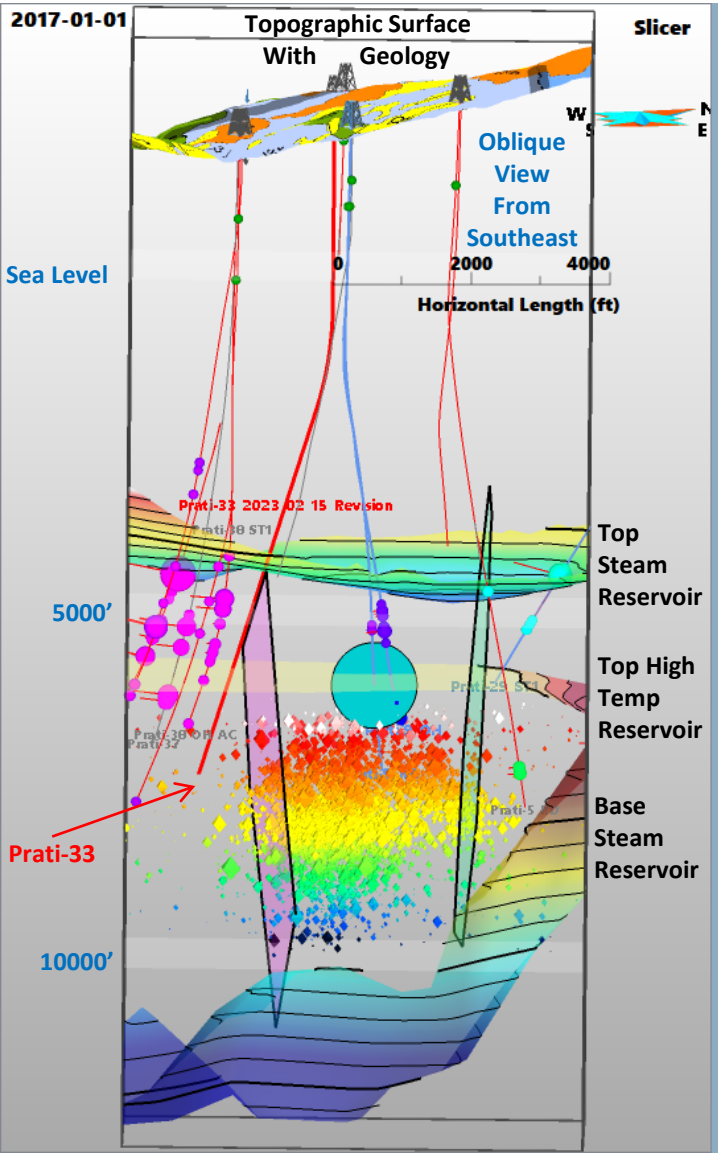
North Geysers Induced Seismicity Animation
VIDEO: 01 January 2008 To 01 January 2017

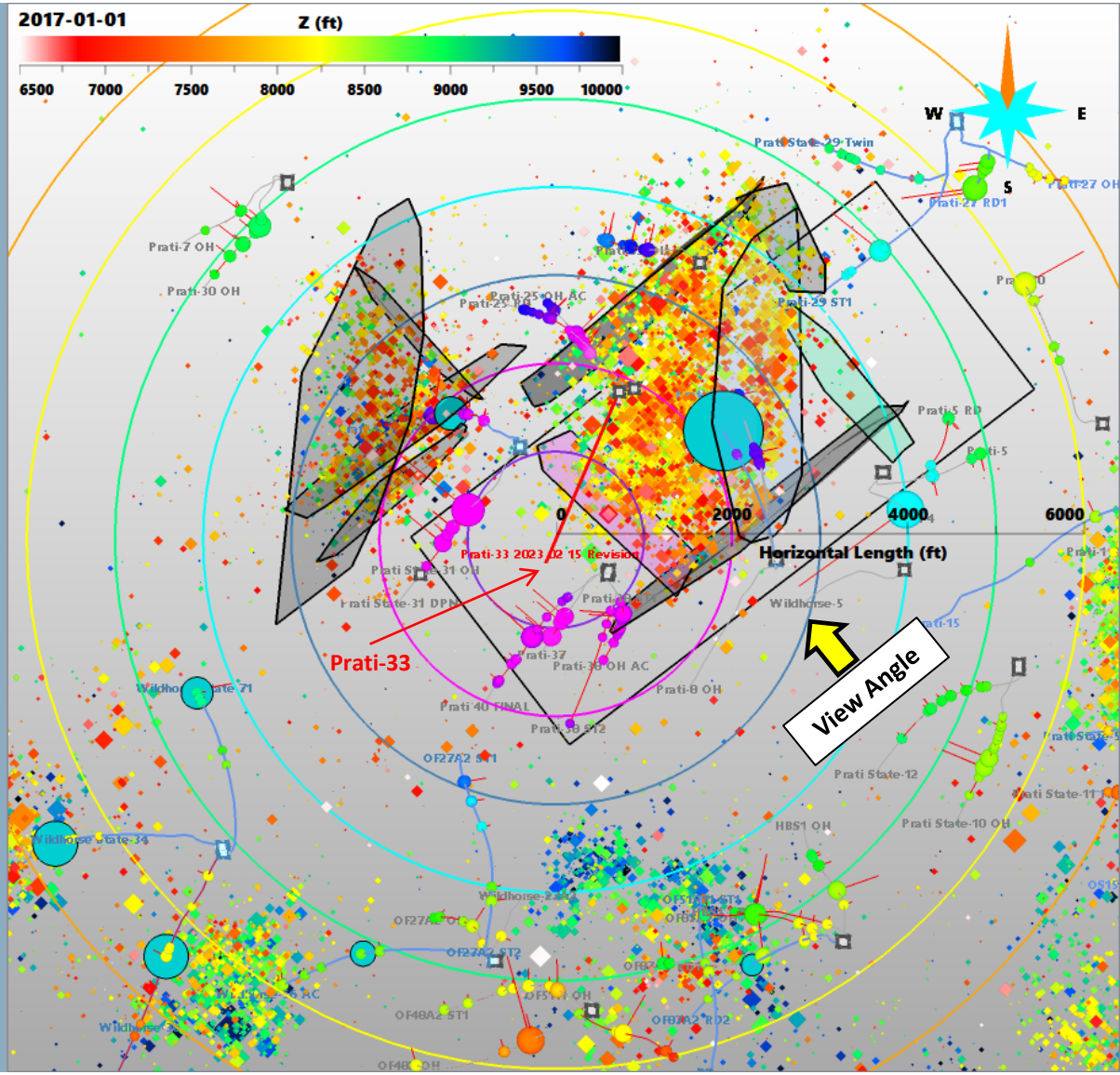
Steam Entries On Well Trajectories
Pressure Increase Proportional To Sphere Size
Separation Distances Visualized By Sphere Color



North Geysers Induced Seismicity
IMAGE: 01 January 2008 To 01 January 2017

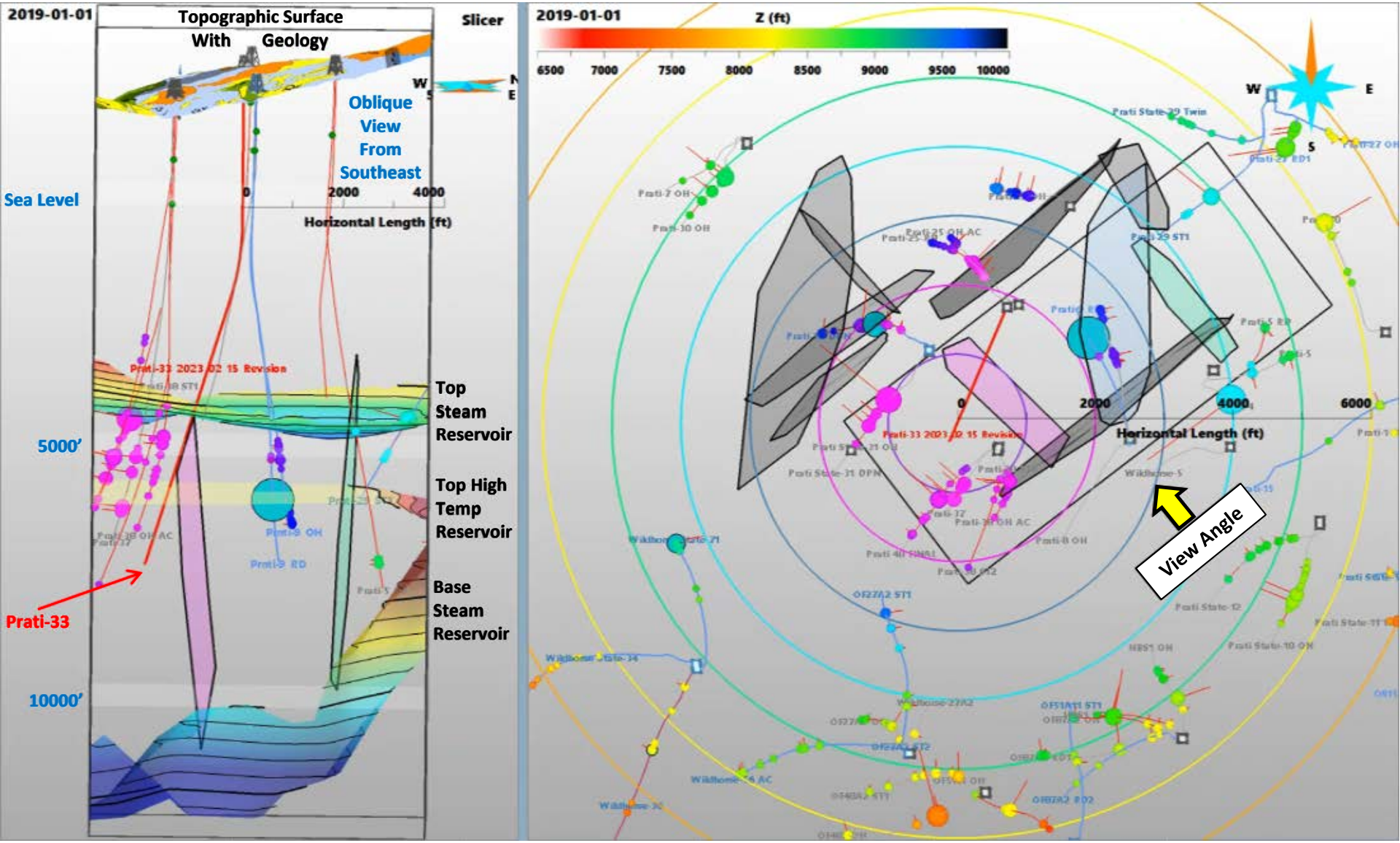
Steam Entries On Well Trajectories
Pressure Increase Proportional To Sphere Size
Separation Distances Visualized By Sphere Color





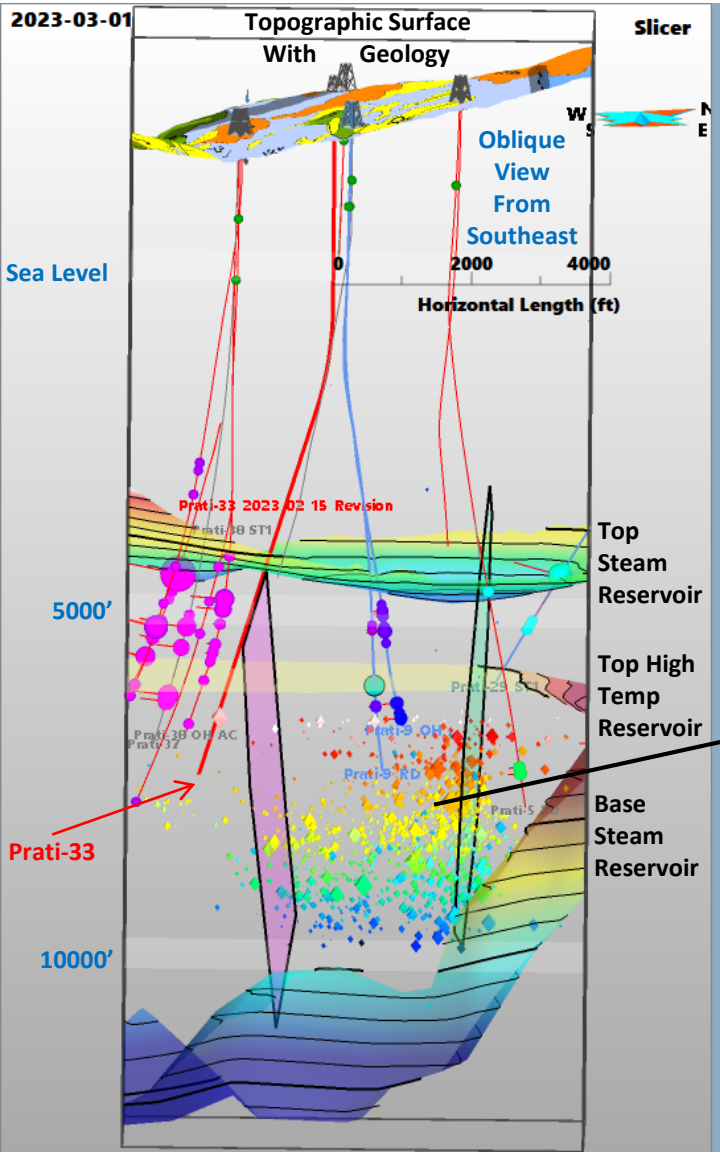
North Geysers Induced Seismicity Animation
VIDEO: 01 January 2019 To 01 March 2023

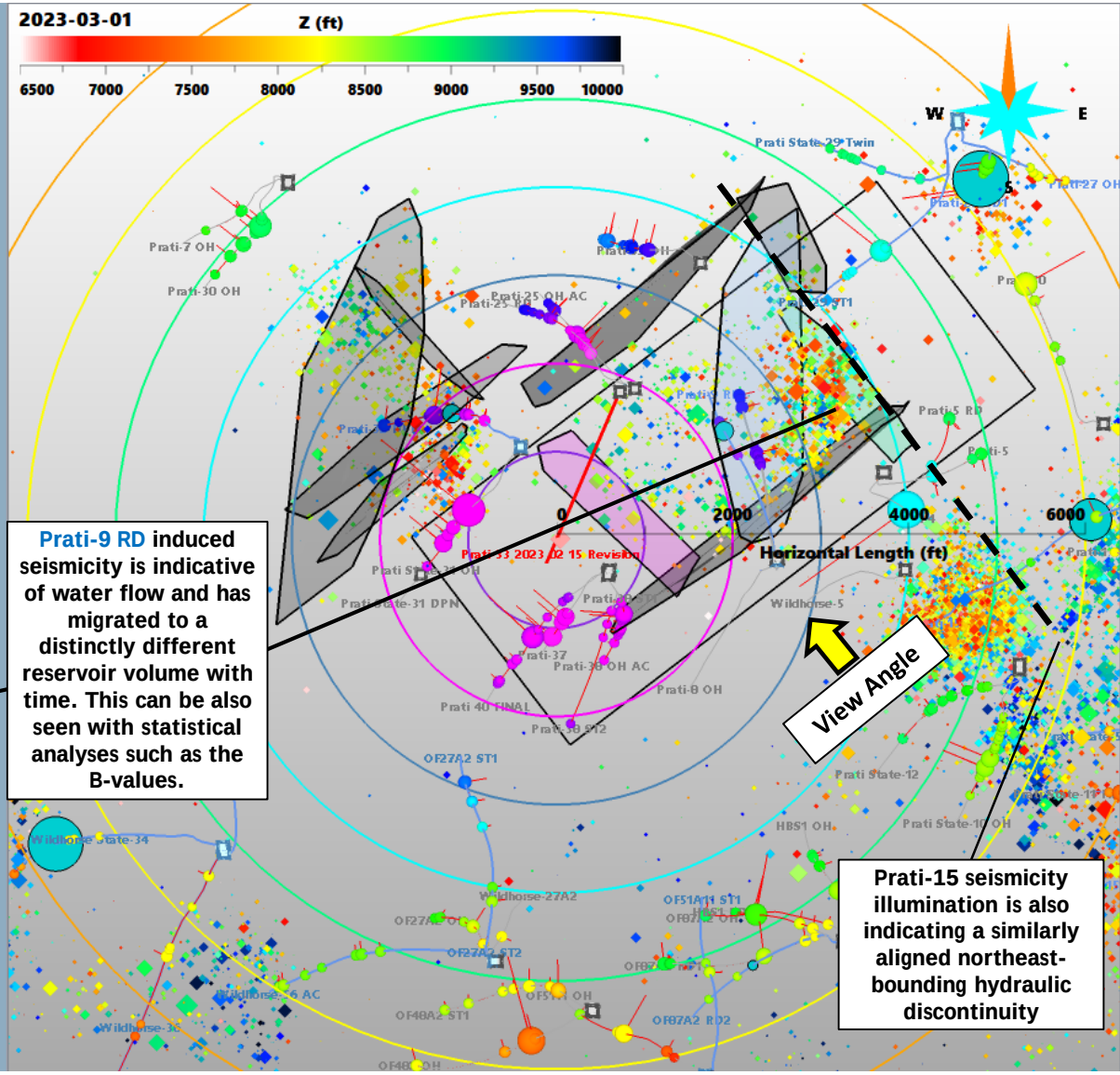
Steam Entries On Well Trajectories
Pressure Increase Proportional To Sphere Size
Separation Distances Visualized By Sphere Color



North Geysers Induced Seismicity
IMAGE: 01 January 2019 To 01 March 2023

Steam Entries On Well Trajectories
Pressure Increase Proportional To Sphere Size
Separation Distances Visualized By Sphere Color



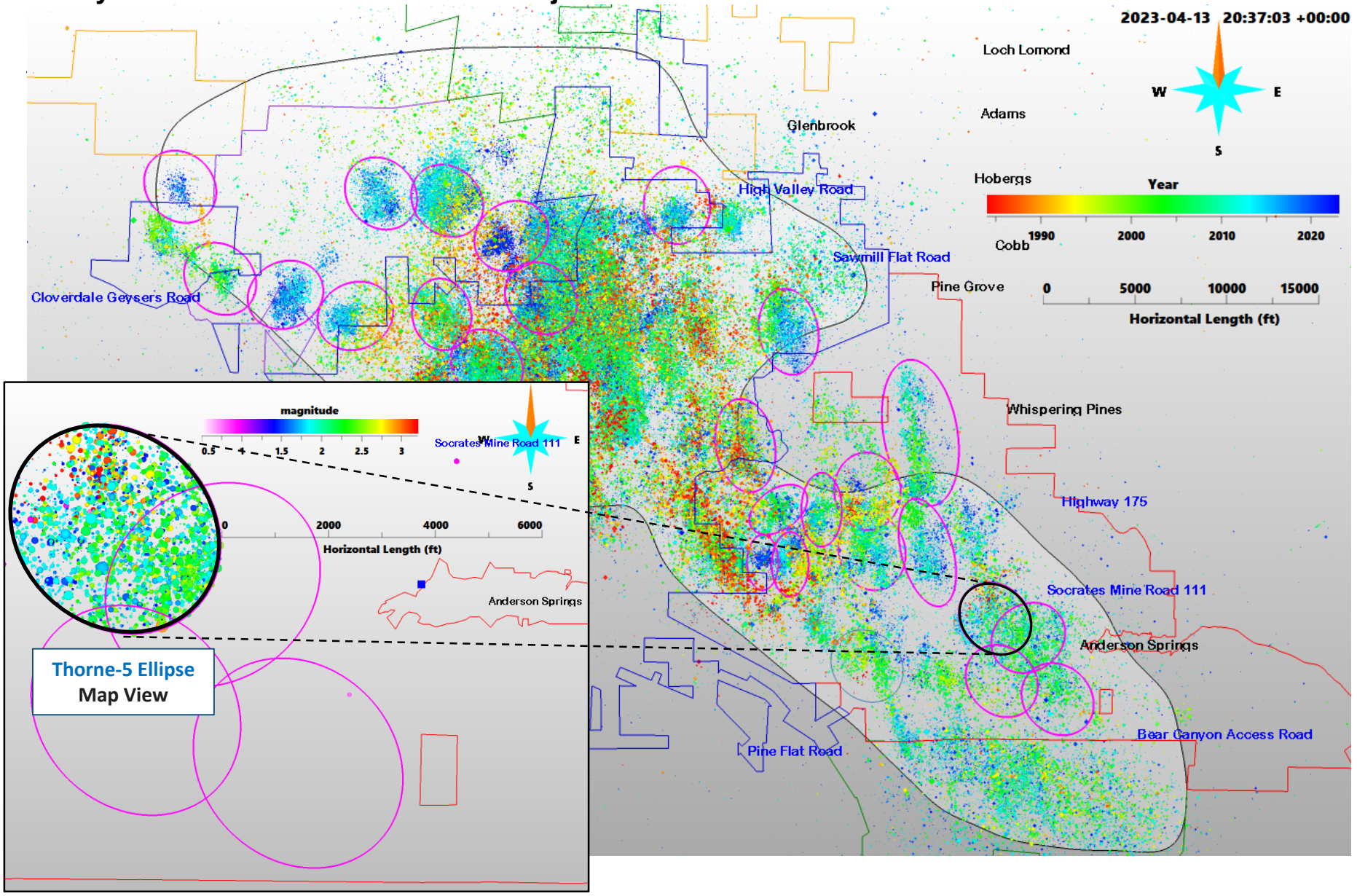


Prati-9 RD induced seismicity is indicative of water flow and has migrated to a distinctly different reservoir volume with time. This can be also seen with statistical analyses such as the B-values.

Prati-15 seismicity illumination is also indicating a similarly aligned northeast-bounding hydraulic discontinuity

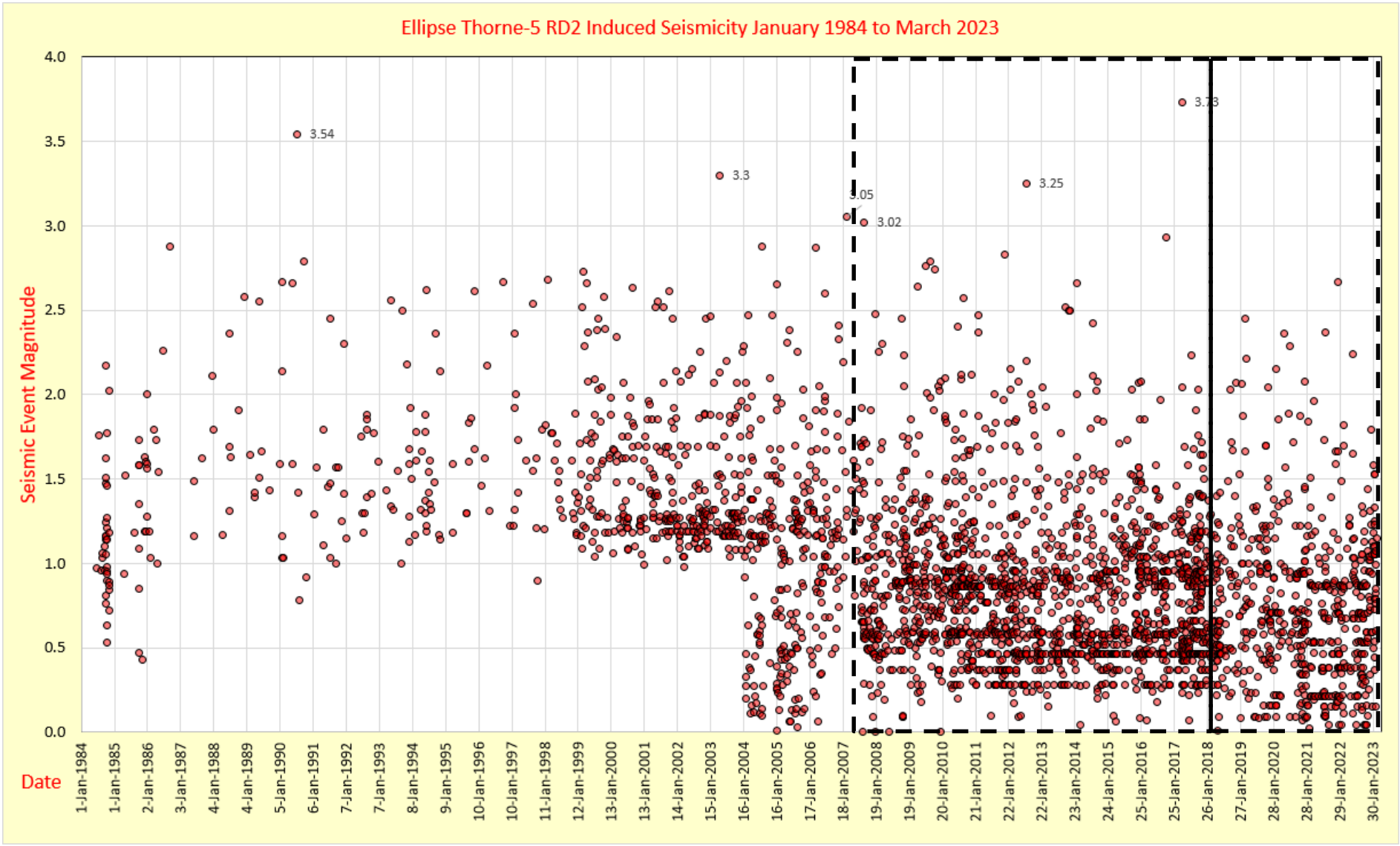
Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Area Of Influence for Individual Water Injection Wells Determined



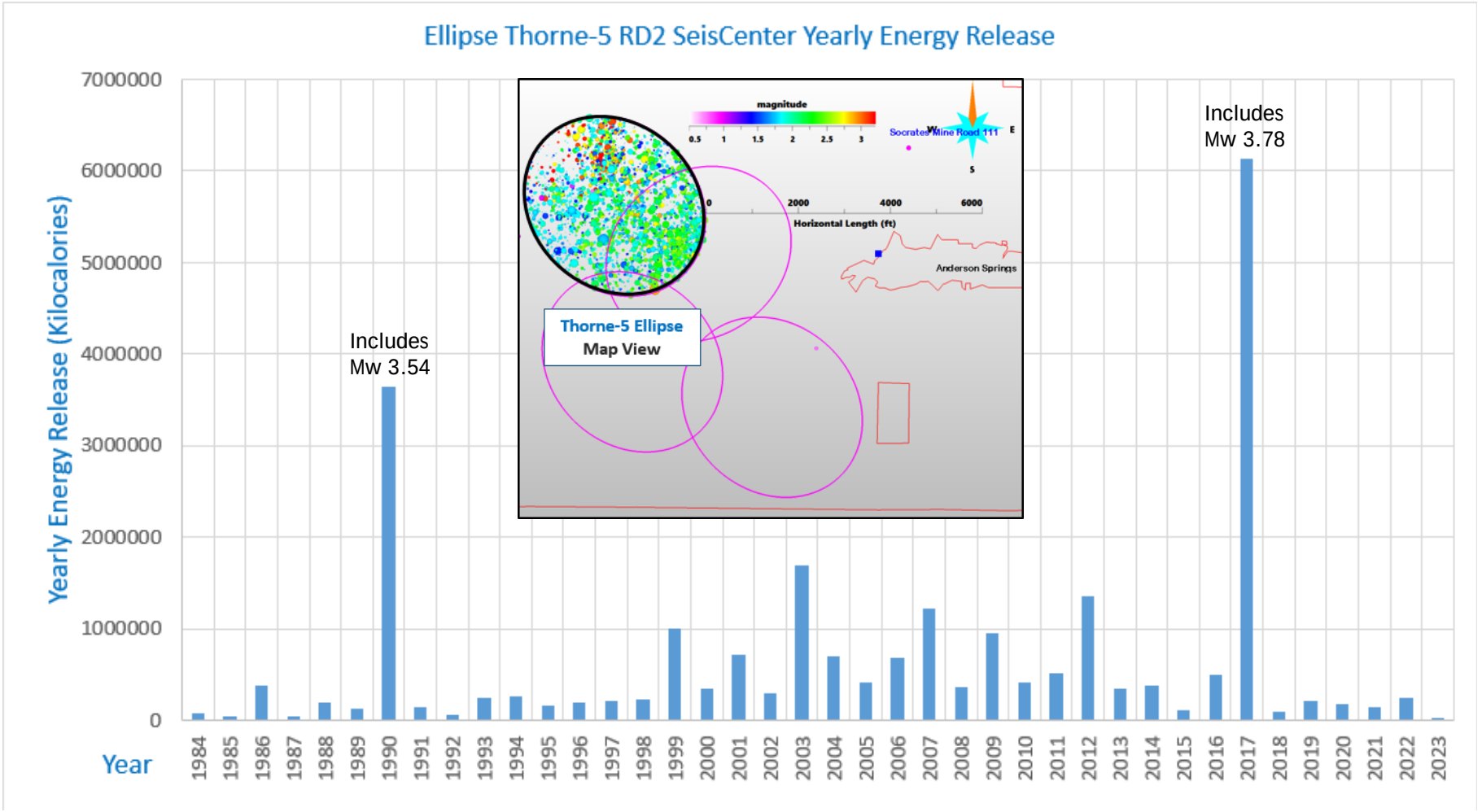
Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Influence By Well Thorne-5 RS2 Well In Southeast Geysers



Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

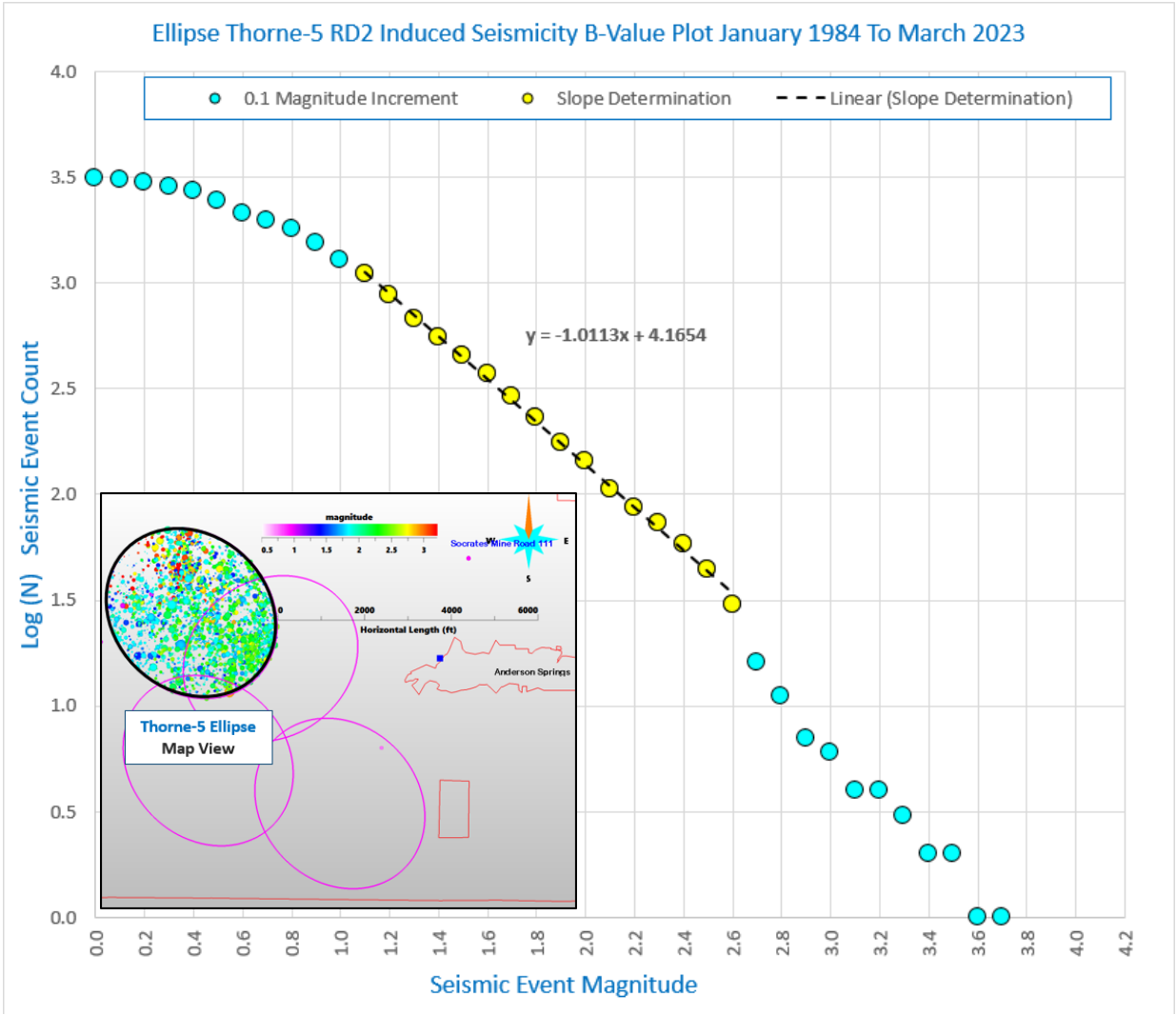
Primary Influence By Well Thorne-5 RD2 In Southeast Geysers



Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Influence By Well Thorne-5 RD2

B-Values For Interval January 1984 To March 2023

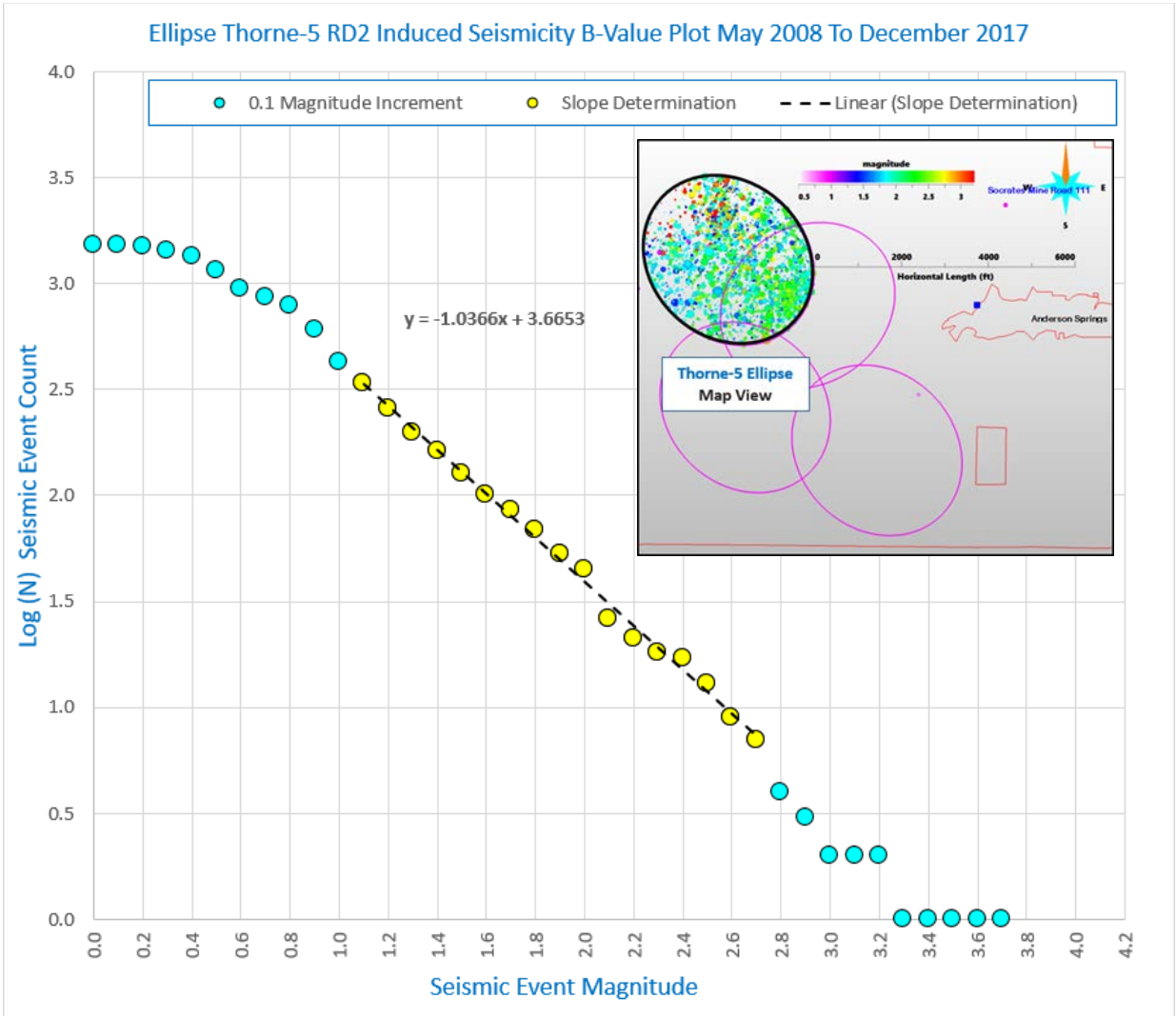


Minimum	>= Min	Log10
0.00	3098	3.49
0.10	3056	3.49
0.20	3000	3.48
0.30	2847	3.45
0.40	2717	3.43
0.50	2438	3.39
0.60	2127	3.33
0.70	1957	3.29
0.80	1806	3.26
0.90	1545	3.19
1.00	1290	3.11
1.10	1101	3.04
1.20	877	2.94
1.30	675	2.83
1.40	550	2.74
1.50	452	2.66
1.60	371	2.57
1.70	291	2.46
1.80	230	2.36
1.90	174	2.24
2.00	144	2.16
2.10	105	2.02
2.20	87	1.94
2.30	73	1.86
2.40	58	1.76
2.50	44	1.64
2.60	30	1.48
2.70	16	1.20
2.80	11	1.04
2.90	7	0.85
3.00	6	0.78
3.10	4	0.60
3.20	4	0.60
3.30	3	0.48
3.40	2	0.30
3.50	2	0.30
3.60	1	0.00
3.70	1	0.00

Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Influence By Well Thorne-5 RD2

B-Values For Interval May 2008 To December 2017

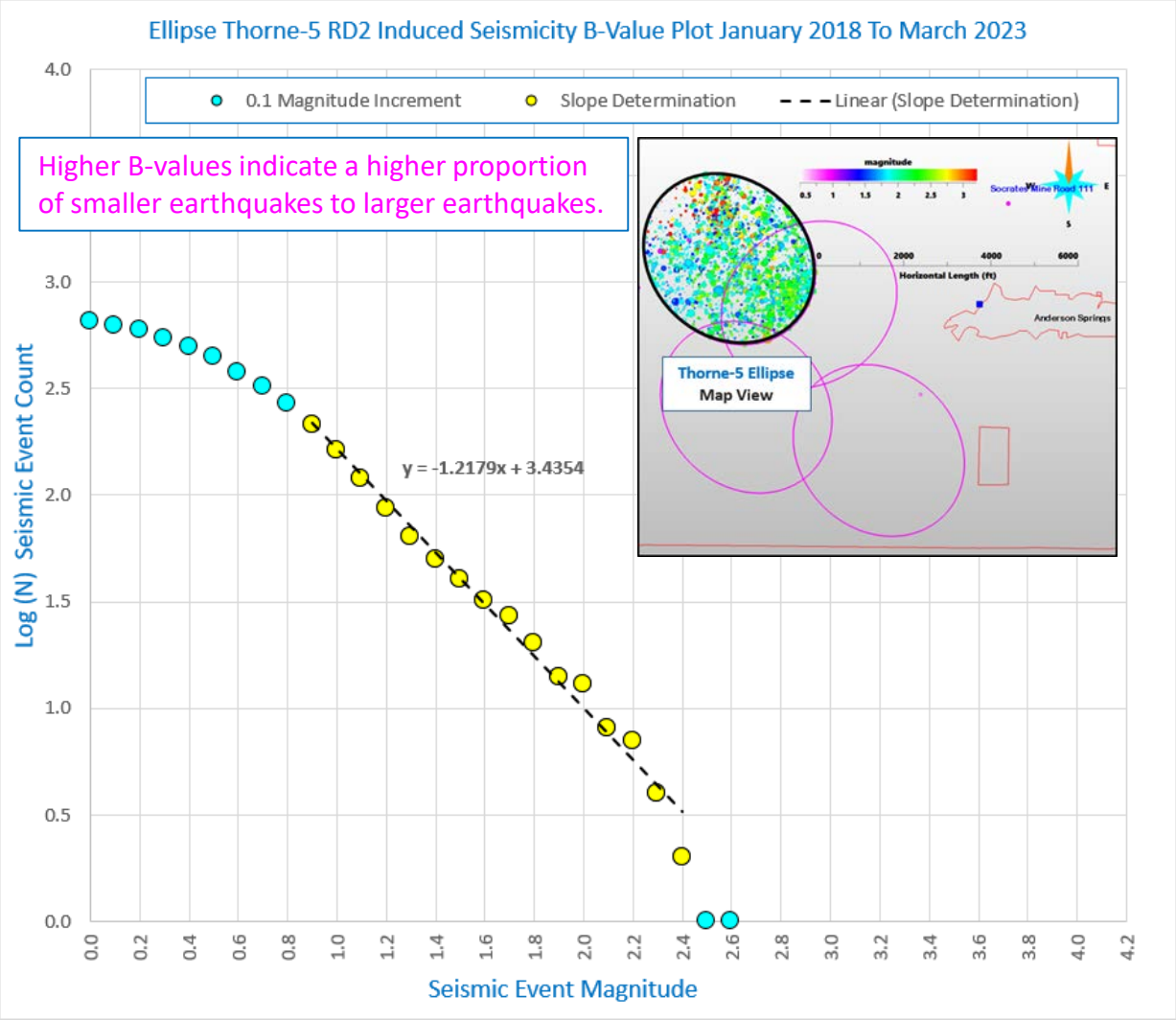


Minimum	>= Min	Log10
0.00	1521	3.18
0.10	1511	3.18
0.20	1503	3.18
0.30	1420	3.15
0.40	1348	3.13
0.50	1151	3.06
0.60	945	2.98
0.70	856	2.93
0.80	781	2.89
0.90	603	2.78
1.00	428	2.63
1.10	338	2.53
1.20	258	2.41
1.30	199	2.30
1.40	161	2.21
1.50	126	2.10
1.60	100	2.00
1.70	85	1.93
1.80	69	1.84
1.90	53	1.72
2.00	45	1.65
2.10	26	1.41
2.20	21	1.32
2.30	18	1.26
2.40	17	1.23
2.50	13	1.11
2.60	9	0.95
2.70	7	0.85
2.80	4	0.60
2.90	3	0.48
3.00	2	0.30
3.10	2	0.30
3.20	2	0.30
3.30	1	0.00
3.40	1	0.00
3.50	1	0.00
3.60	1	0.00
3.70	1	0.00

Analysis Of Individual Wells: Water Injection and Induced Seismicity Relationships

Primary Influence By Well Thorne-5 RD2

B-Values For Interval January 2018 To March 2023

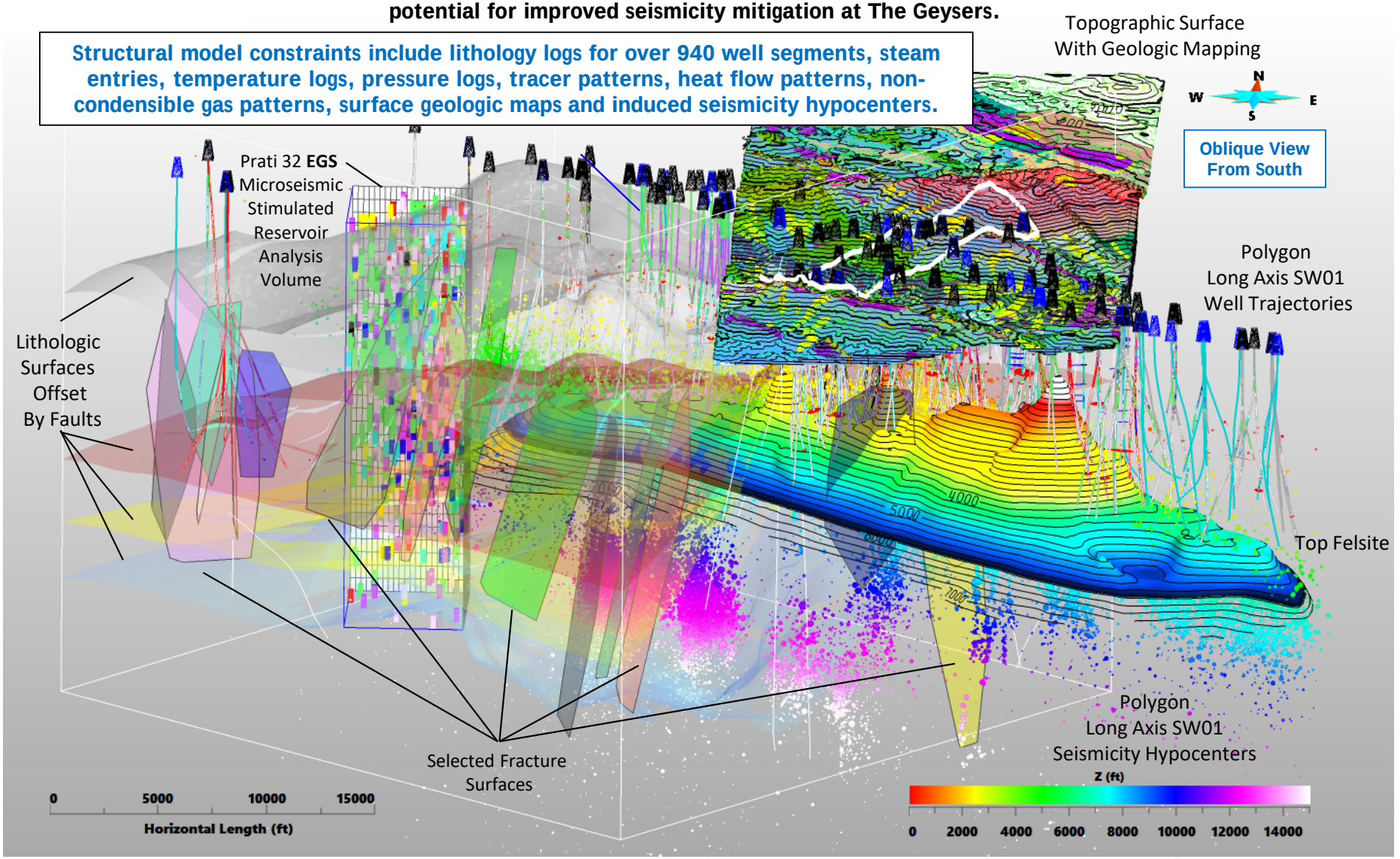


Minimum	>= Min	Log10
0.00	650	2.81
0.10	626	2.80
0.20	593	2.77
0.30	542	2.73
0.40	497	2.70
0.50	445	2.65
0.60	376	2.58
0.70	324	2.51
0.80	268	2.43
0.90	215	2.33
1.00	162	2.21
1.10	119	2.08
1.20	87	1.94
1.30	64	1.81
1.40	50	1.70
1.50	40	1.60
1.60	32	1.51
1.70	27	1.43
1.80	20	1.30
1.90	14	1.15
2.00	13	1.11
2.10	8	0.90
2.20	7	0.85
2.30	4	0.60
2.40	2	0.30
2.50	1	0.00
2.60	1	0.00

The Geysers Fieldwide 3D Structural Model

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

Structural model constraints include lithology logs for over 940 well segments, steam entries, temperature logs, pressure logs, tracer patterns, heat flow patterns, non-condensible gas patterns, surface geologic maps and induced seismicity hypocenters.




CALPINE®


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