SNT Satellite Update
InSAR Subsidence
October 28, 2023

<u>Lonquist comment:</u>

The SNT satellite (12-day revisit) passed by Sulphur on Saturday October 28. We received the dataset Monday and verified that none of the datapoint areas around the dome and caverns near the western flank are showing deviation from their respective trends. The attached evaluation report has been prepared for reference.

Submitted by: Nathaniel Byars (Lonquist)

SNT Satellite Update

Continuous InSAR Monitoring of
Ground Displacement
Near Western Caverns and Dome Flank

Sulphur Mines Salt Dome

Prepared for:
Westlake Chemical

Prepared by:
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Baton Rouge, LA 70809

Dataset
Satellite Source
Sentinel-1 (SNT)
Most Recent Image Date
Saturday, October 28, 2023

Analysis Report Date:

November 1, 2023

Dataset Information

Satellite Source	Sentinel-1 (SNT)
Revisit Frequency	12 days
Most Recent Image Date	Saturday, October 28, 2023
Dataset Image Count	190
Dataset Time Range	October 4, 2016 - October 28, 2023
Dataset Length	7.06 Years
Satellite Line-of-Sight (LOS)	43° West of Vertical (Viewing site from the West)

Analysis Methodology

Time Series Charts

Trend lines were calculated for the averaged displacement values within each AOI. Quadratic regression was used to determine Velocity and Acceleration of LOS displacement. Trends calculated for the AOI point groups are depicted for each AOI in the Time Series section of this report.

Contour Maps

A quadratic trend was also calculated for each individual measurement point across the analysis region. Trend values for each point were used to generate Velocity and Acceleration contour maps to depict the spatial distribution of the movement trends. Negative velocity values indicate subsidence. Negative acceleration values indicate increasing rates of subsidence and positive acceleration values indicate slowing rates of subsidence.

Recent vs. Historical Data

The multi-year SNT dataset timeframe allows for Recent data to be evaluated separately from Historical data and for trends from the two timeframes to be compared. The change in the velocities and accelerations from the two timeframes are provided in the Time Series and Contour Map sections. Velocity values are calculated for the final date in either the Recent or Historical datasets.

Observations

To-date there have been no acute deviations from established subsidence trends in the areas investigated.

The comparison of Recent to Historical trends in the SNT data does imply a minor increase in the negative velocity and negative acceleration of LOS displacement in AOI 1, AOI 2, AOI 3, AOI 6 (PPG 6), AOI 7 (PPG 7), AOI 8 (PPG 22), and AOI 9 (SMS A1). This suggests that marginal increases in subsidence rates may be occuring in these areas in recent years with the greatest increase occuring in AOI 8.

In the mapped contours of the change in recent vs. historical subsidence rates, the greatest change is seen to be occuring in AOI 8 (PPG 22) and moderate increases in subsidence rates are seen in all but AOI 4 and AOI 5 (PPG 21), in both the velocity and acceleration maps. This supports the average trend change values presented in the AOI Analysis Summary.

Date Signed: November 1, 2023
Austin, Texas

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Principal Engineer
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InSAR Data Sources

InSAR Data

Interferometric Synthetic Aperture Radar (InSAR) is the most well established method to continually evaluate small, normally undetectable, ground movement over a large area. Radar imagery collected via satellites over successive orbital passes is used to identify and define measurement points on the ground. Objects or ground features providing a stable reflection of radar energy such as buildings, roads, and infrastructure produce the highest quality measurement points. InSAR analysis identifies the change in distance between the satellite and each measurement point over time relative to a stable reference point within the imaged area.

Satellite Sources

Two InSAR datasets are being used to evaluate subsidence over the Sulphur Mines Salt Dome. These datasets provide Line-of-Sight (LOS) displacement measurements from both ascending and descending orbits. An ascending orbit denotes the satellite's longitudinal course from south to north as it passes over the site, while a desceding orbit denotes the satellite is moving from north to south.

The first dataset comes from a low-resolution Sentinel-1 (SNT) satellite on an ascending orbit that captures data from the west of the site on a 12-day frequency. The second comes from a pair of high resolution satellites that share the same descending orbit and capture data from east of the site. These are a TSX satellite and the PAZ satellite (TSX/PAZ constellation), both with an 11-day revisit frequency. Their orbits are offset with the PAZ satellite passing over the site 4 days after the TSX satellite. Prior to May 2023, data was captured from a different high-resolution TerraSAR-X (TSX) satellite on a descending orbit that captured data from the east of the site on an 11-day frequency. The transition was made for the increased data frequency that resulted from a 4 and 7-day revisit period. The image below depicts the orbital paths of the satellites in relation to the Sulphur Mines Salt Dome.

Satellite Orbital Diagram
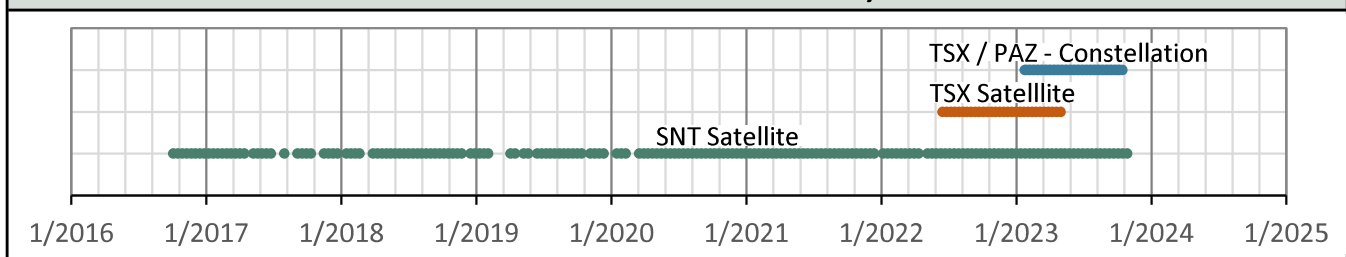
InSAR Line-of-Site (LOS) Data

LOS displacement measurements refer to a change in distance between the satellite sensor and the ground target. Measurement positions on the west side of the Sulphur Dome are are known to be experiencing some eastward movement toward the dome center due to the geometry of the subsidence basin. The InSAR satellites view the site from eastward and westward positions so LOS measurements are understood to convey a movement distance that is not purely vertical. The diagram to the right illustrates the geometric relationship between the theoretical Real movement of a ground target and LOS displacement measurements from two different satellite viewing directions.
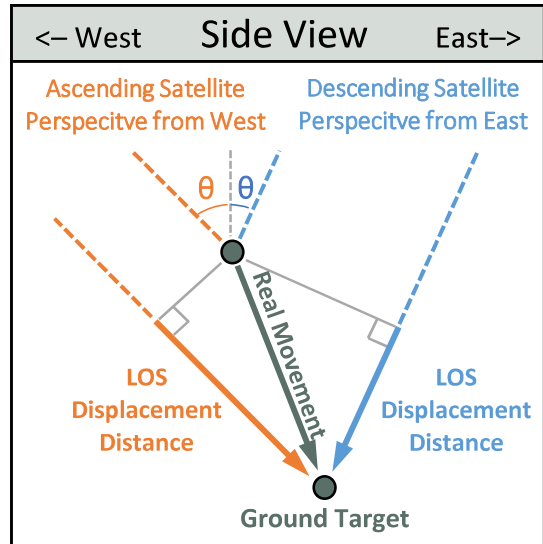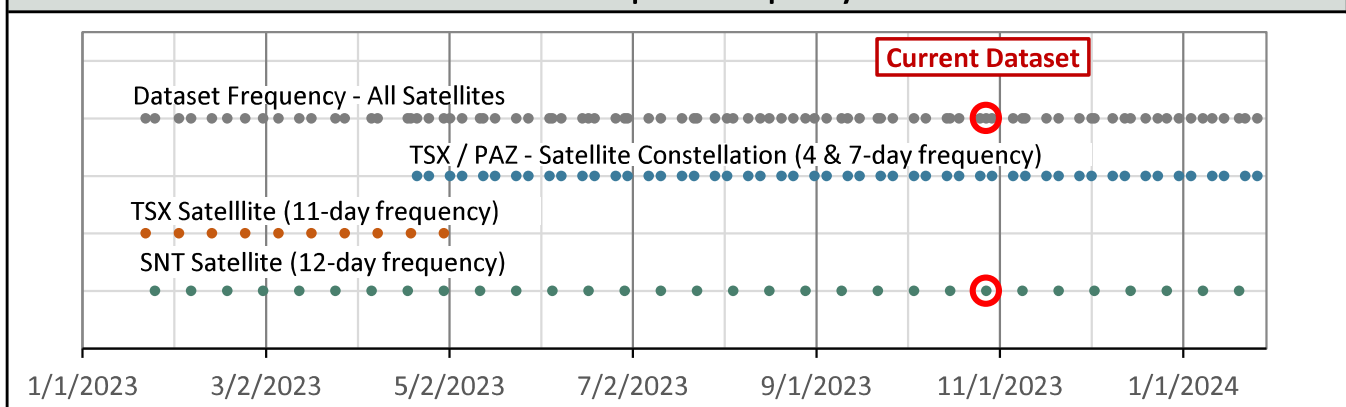

Satellite Properties & Image Frequency

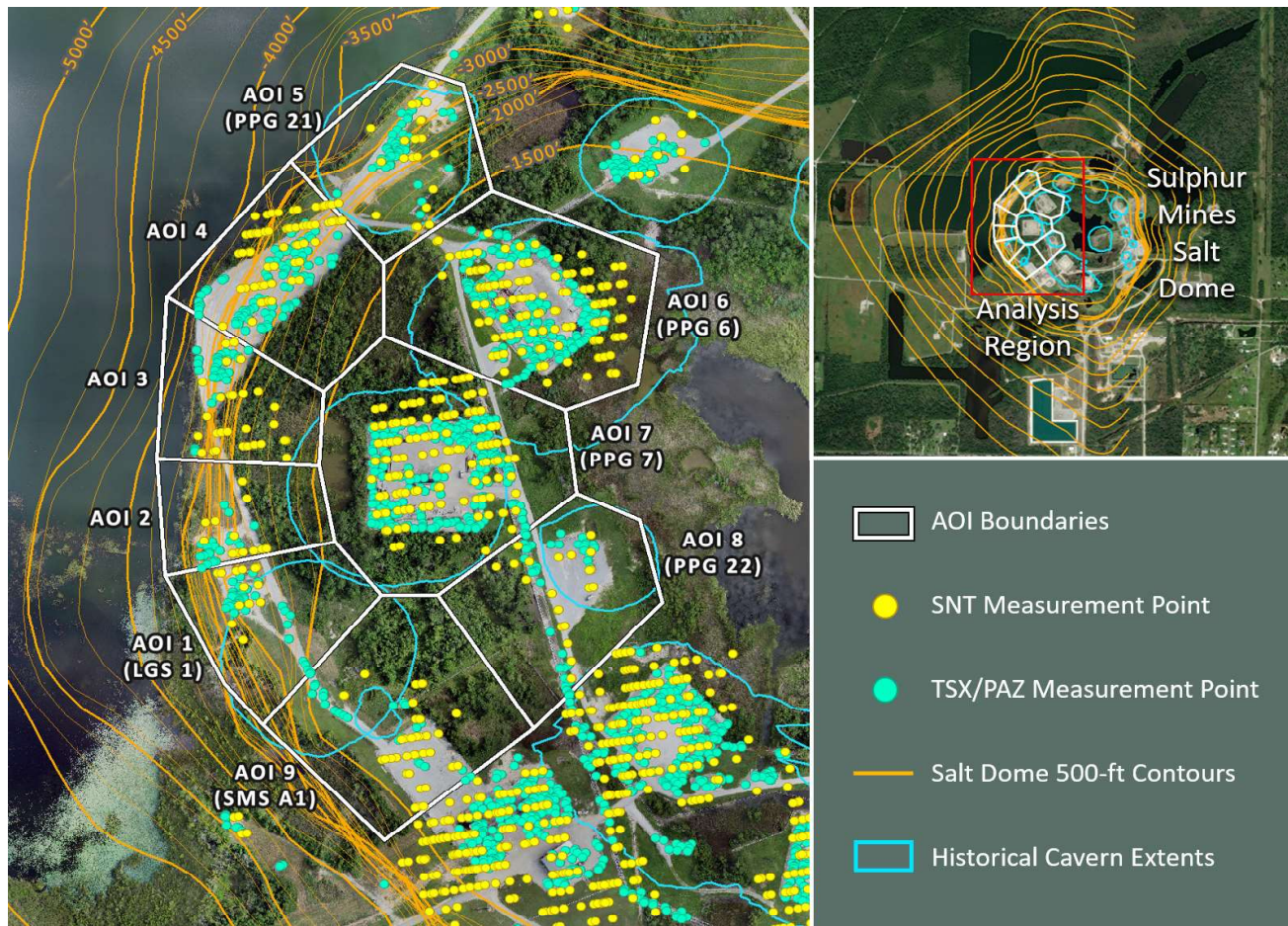| Satellite and Data Properties	SNT	TSX	TSX/PAZ Constellation
Band (Wavelength)	C-band (2.20 in)	X-band (1.22 in)	X-band (1.22 in)
Track	T136	T29	T67 & T120
Pixel resolution	65 x 16 ft	3 x 3 ft	3 x 3 ft
Revisit frequency	12 days	11 days	4 & 7 days
Orbit (LOS Angle, θ)	Ascending (43°)	Descending (17°)	Descending (37°)
Data Start Date	10/4/2016	6/16/2022	1/24/2023
Measurement error range	± 0.20 in	± 0.03 in	± 0.03 in

Dataset Measurement History

Dataset Update Frequency

AOI Boundaries & InSAR Measurement Points

AOI 5
(PPG 21)

AOI 4

AOI 3

AOI 2

AOI 1
(LGS 1)

AOI 6
(PPG 6)

AOI 7
(PPG 7)

AOI 8
(PPG 22)

AOI 9
(SMS A1)

Sulphur
Mines
Salt
Dome

Analysis
Region

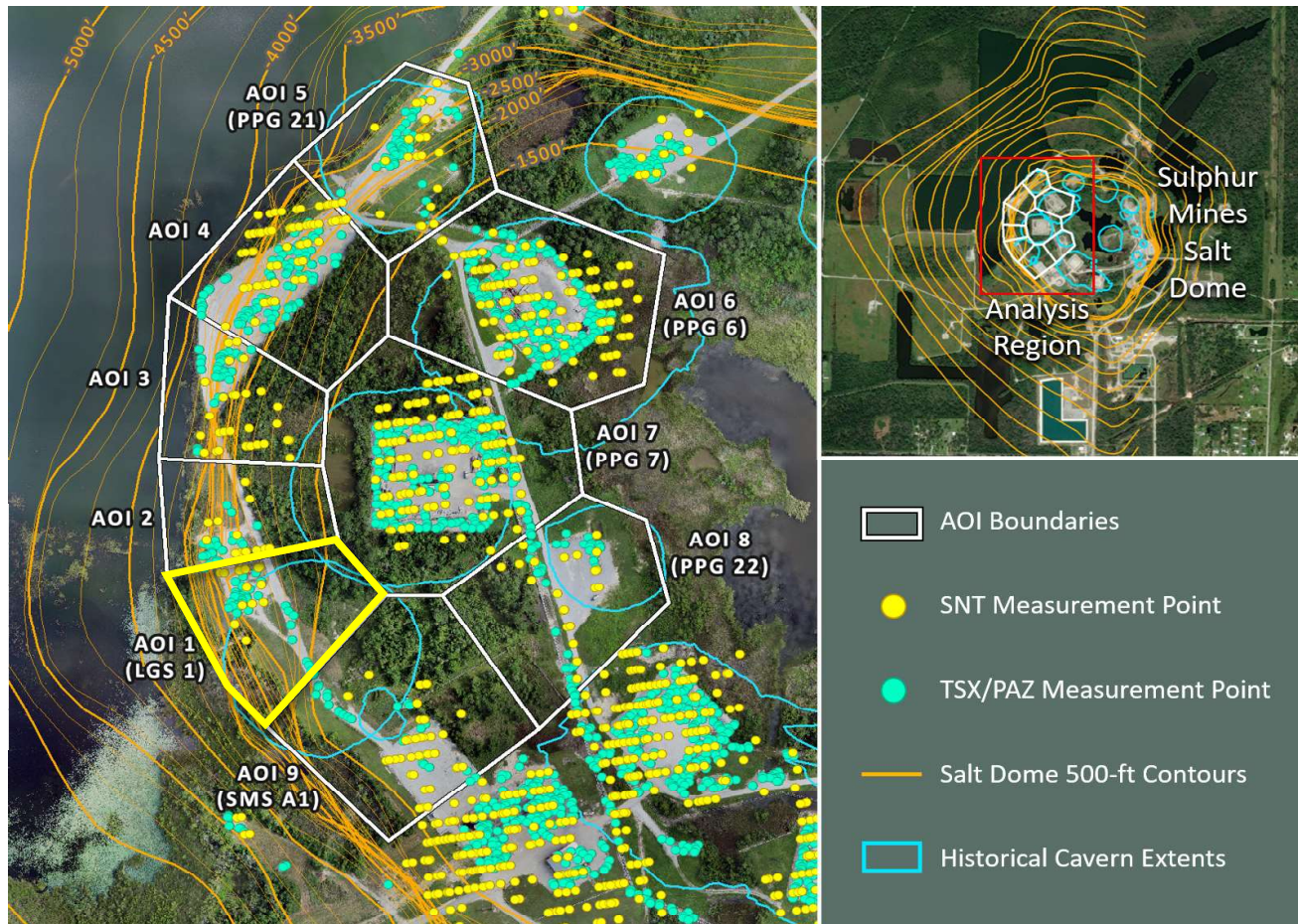|	
▭	AOI Boundaries
●	SNT Measurement Point
●	TSX/PAZ Measurement Point
—	Salt Dome 500-ft Contours
▭	Historical Cavern Extents

Subsidence Monitoring Areas of Interest (AOIs)

To visually convey and evaluate trend consistency for the displacement time series of each ground target, measurment points were grouped and their displacement values were averaged. The point groups are referred to as Areas of Interest (AOIs) in this analysis and their boundaries are depicted on the above map. The below table lists the trend values calculated in each AOI for the dataset evaluated in this report.
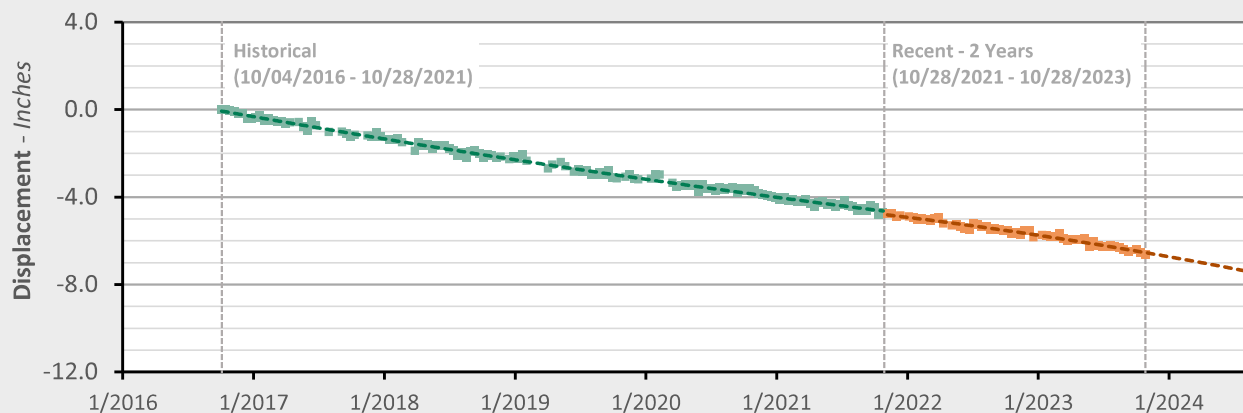
AOI Name	SNT (10/28/2023)	LOS Velocity *(in/yr)*			LOS Acceleration *(in/yr^2)*		
	Point Count	Historical	Recent	Change	Historical	Recent	Change
AOI 1 *(LGS 1)*	13	-0.74	-1.03	-0.29	+0.06	-0.16	-0.22
AOI 2	15	-0.74	-1.11	-0.37	+0.08	-0.12	-0.21
AOI 3	29	-0.65	-0.93	-0.28	+0.04	-0.24	-0.28
AOI 4	63	-0.73	-0.68	+0.05	+0.02	+0.02	+0.00
AOI 5 *(PPG 21)*	24	-0.67	-0.52	+0.15	+0.02	+0.08	+0.07
AOI 6 *(PPG 6)*	134	-0.87	-0.95	-0.08	+0.06	-0.04	-0.10
AOI 7 *(PPG 7)*	140	-0.99	-1.26	-0.27	+0.09	-0.15	-0.24
AOI 8 *(PPG 22)*	21	-1.06	-1.50	-0.44	+0.13	-0.25	-0.38
AOI 9 *(SMS A1)*	39	-0.79	-1.04	-0.26	+0.10	-0.16	-0.27

AOI 1 *(LGS 1)* - Location Map

AOI Boundaries

● **SNT Measurement Point**

● **TSX/PAZ Measurement Point**

— **Salt Dome 500-ft Contours**

▭ **Historical Cavern Extents**

Sulphur Mines Salt Dome

Analysis Region

AOI 1 *(LGS 1)* - Displacement Time Series   SNT (10/28/2023) Point Count: **13**

Historical
(10/04/2016 - 10/28/2021)

Recent - 2 Years
(10/28/2021 - 10/28/2023)

	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.74 in/yr	-1.03 in/yr	-0.29 in/yr
Acceleration:	+0.06 in/yr^2	-0.16 in/yr^2	-0.22 in/yr^2

■ Historical LOS Displacement Measurement

- - - Historical Trend Line (Quadratic Regression)

■ Recent LOS Displacement Measurement

- - - Historical Trend Line (Quadratic Regression)

AOI 2 - Location Map

- **AOI Boundaries**
- 🟡 **SNT Measurement Point**
- 🟢 **TSX/PAZ Measurement Point**
- ── **Salt Dome 500-ft Contours**
- ── **Historical Cavern Extents**
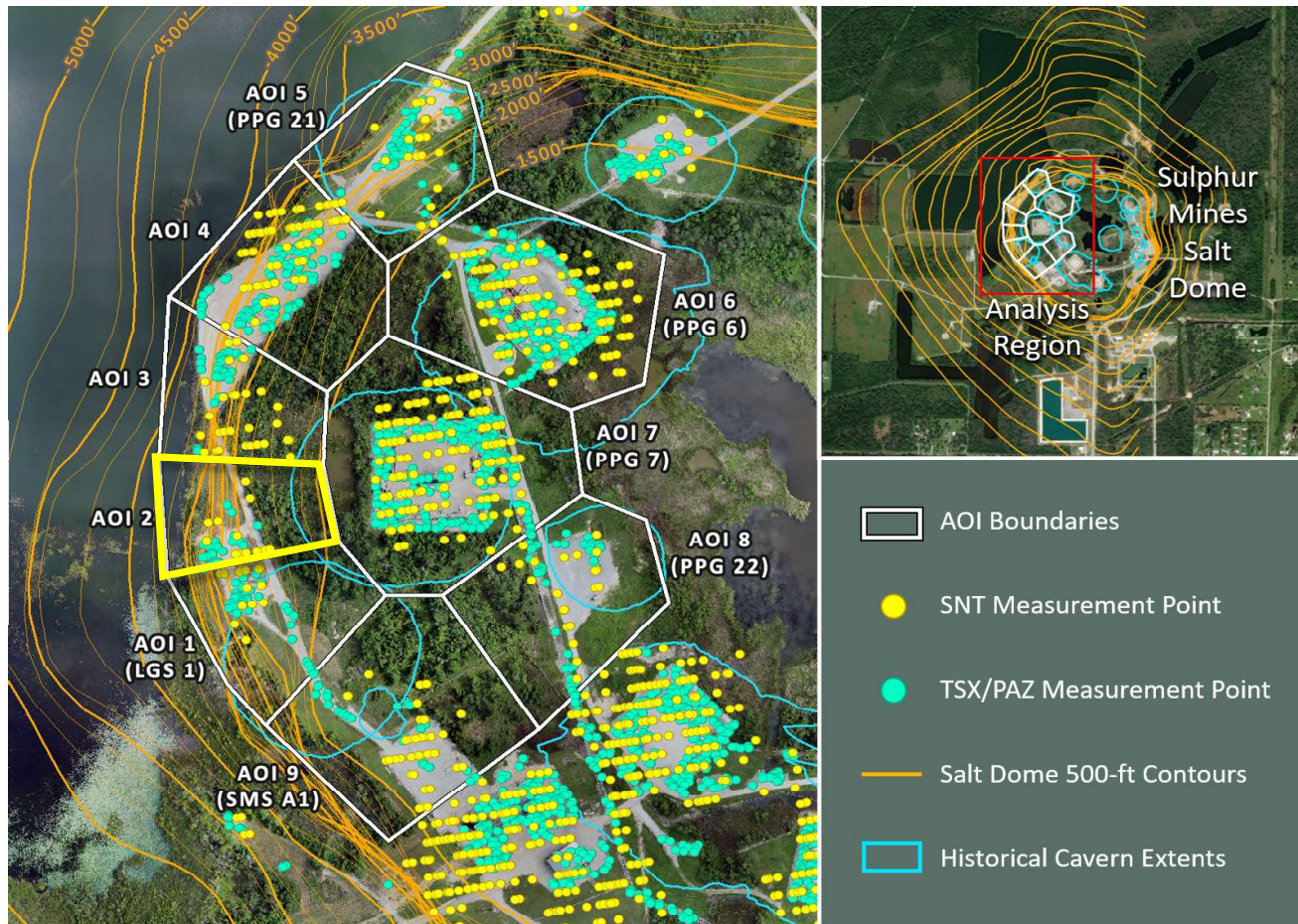
AOI 2 - Displacement Time Series

SNT (10/28/2023) Point Count: 15

Historical
(10/04/2016 - 10/28/2021)

Recent - 2 Years
(10/28/2021 - 10/28/2023)

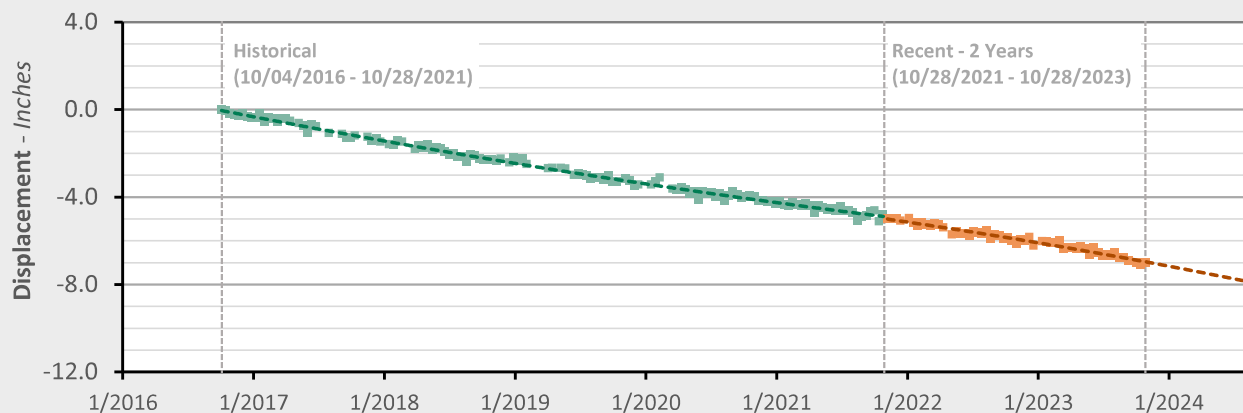|	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.74 in/yr	-1.11 in/yr	-0.37 in/yr
Acceleration:	+0.08 in/yr^2	-0.12 in/yr^2	-0.21 in/yr^2

- ■ Historical LOS Displacement Measurement
- - - Historical Trend Line (Quadratic Regression)
- ■ Recent LOS Displacement Measurement
- - - Historical Trend Line (Quadratic Regression)

AOI 3 - Location Map

Legend:
- ☐ AOI Boundaries
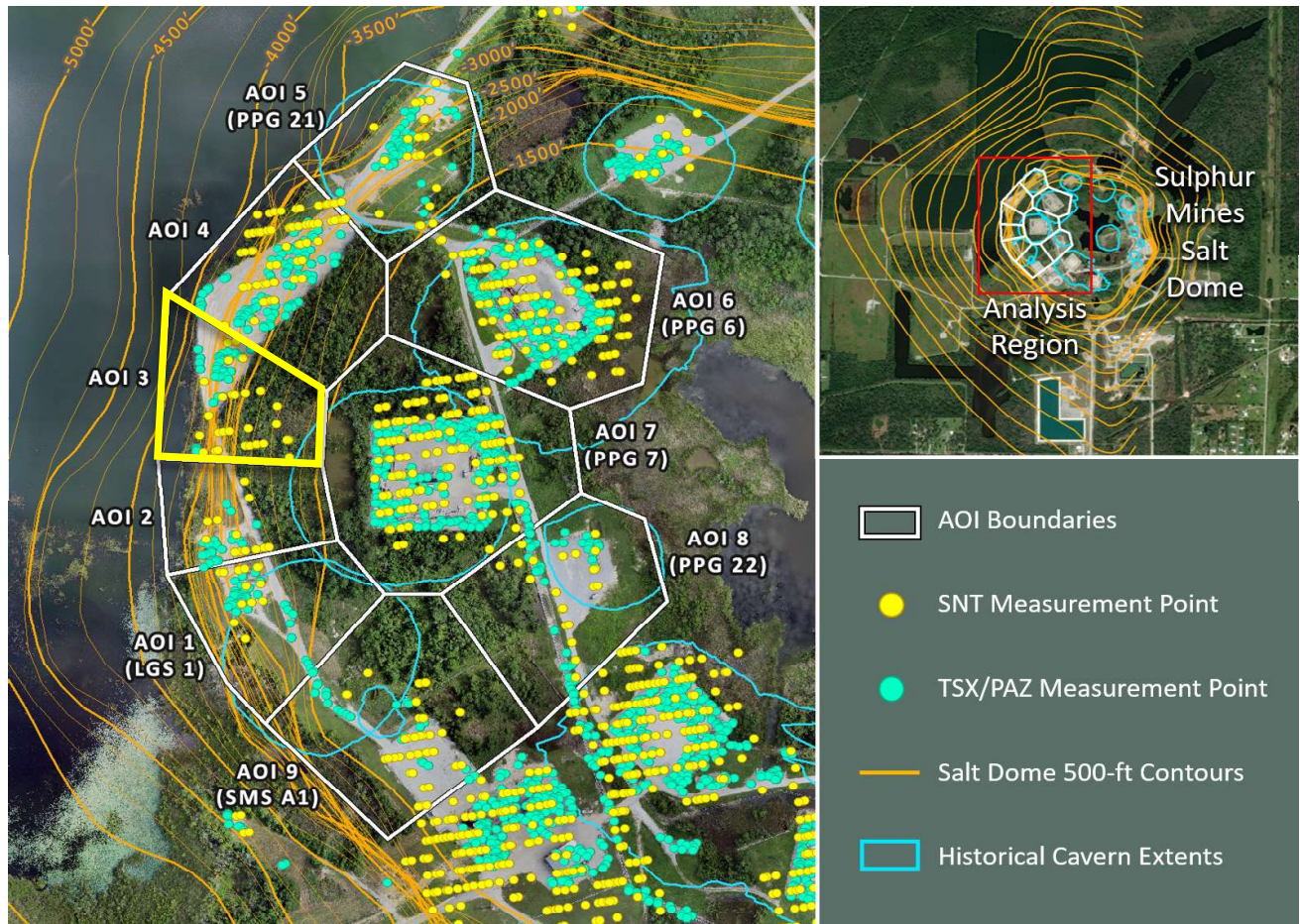- 🟡 SNT Measurement Point
- 🟢 TSX/PAZ Measurement Point
- ― Salt Dome 500-ft Contours
- ― Historical Cavern Extents

AOI 3 - Displacement Time Series

SNT (10/28/2023) Point Count: **29**

Historical (10/04/2016 - 10/28/2021)

Recent - 2 Years (10/28/2021 - 10/28/2023)

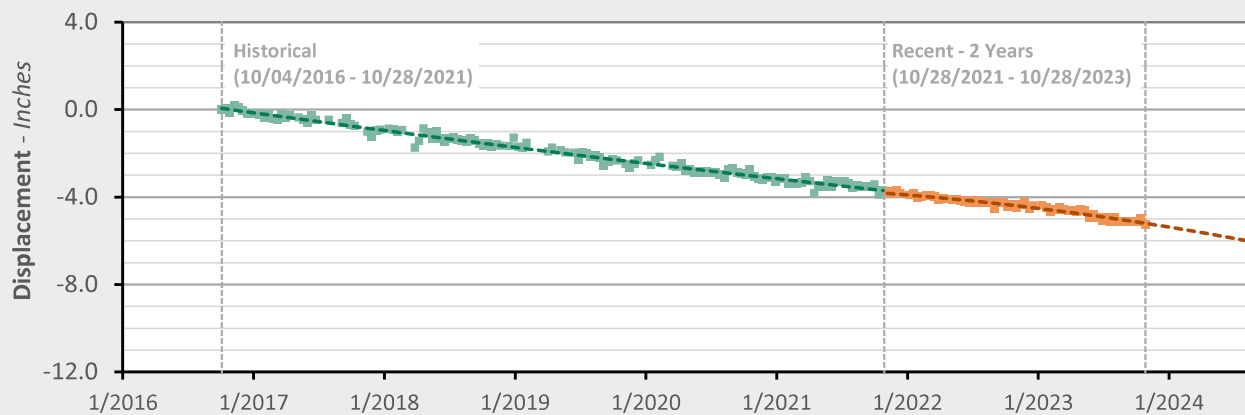|	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.65 in/yr	-0.93 in/yr	-0.28 in/yr
Acceleration:	+0.04 in/yr^2	-0.24 in/yr^2	-0.28 in/yr^2

- ■ Historical LOS Displacement Measurement
- ‒ ‒ Historical Trend Line (Quadratic Regression)
- ■ Recent LOS Displacement Measurement
- ‒ ‒ Historical Trend Line (Quadratic Regression)

AOI 4 - Location Map

AOI 5 (PPG 21)

AOI 4

AOI 3

AOI 2

AOI 1 (LGS 1)

AOI 9 (SMS A1)

AOI 6 (PPG 6)

AOI 7 (PPG 7)

AOI 8 (PPG 22)

Sulphur Mines Salt Dome

Analysis Region

	AOI Boundaries
●	SNT Measurement Point
●	TSX/PAZ Measurement Point
—	Salt Dome 500-ft Contours
—	Historical Cavern Extents

AOI 4 - Displacement Time Series

SNT (10/28/2023) Point Count: **63**

Historical (10/04/2016 - 10/28/2021)

Recent - 2 Years (10/28/2021 - 10/28/2023)

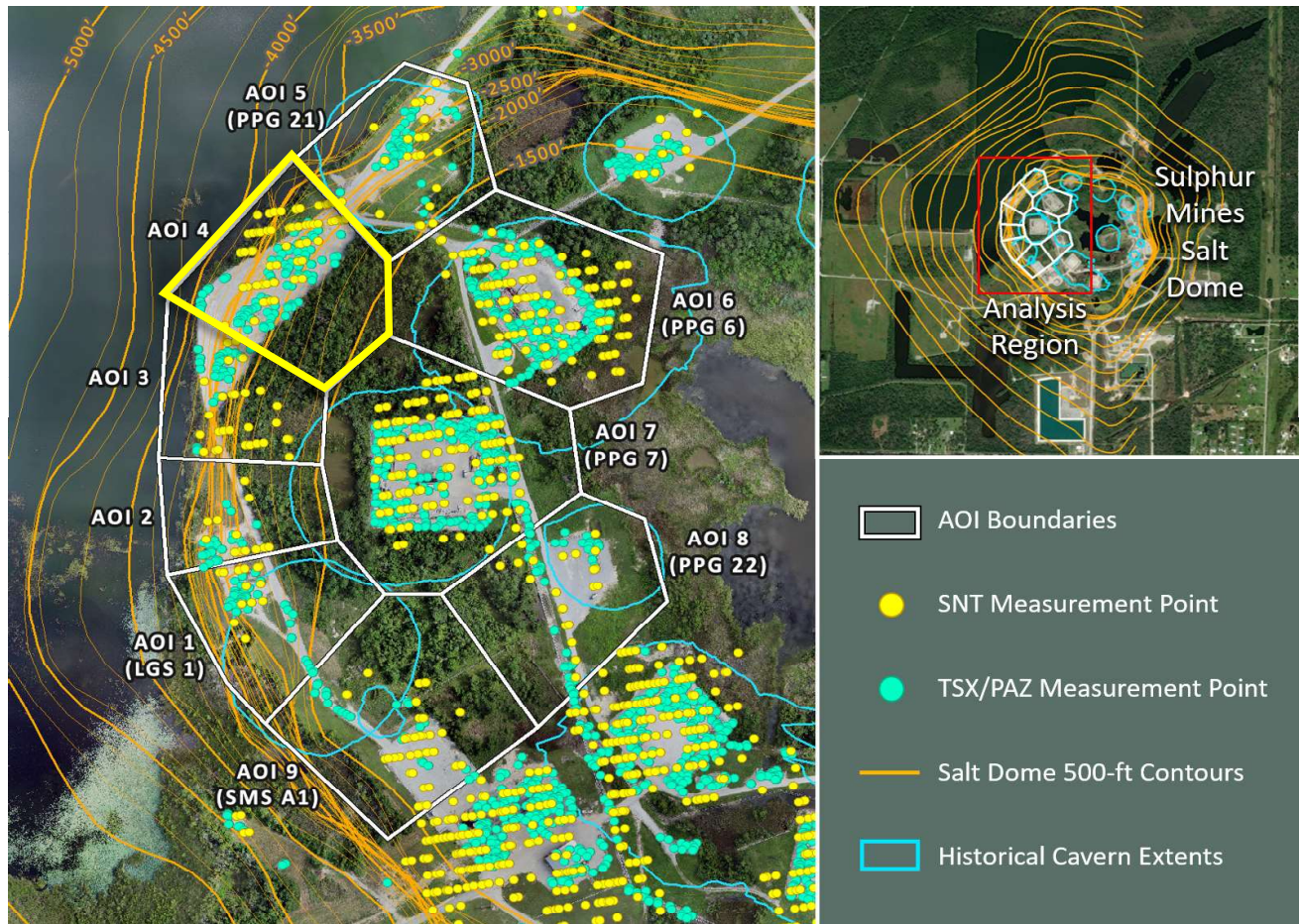|	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.73 in/yr	-0.68 in/yr	+0.05 in/yr
Acceleration:	+0.02 in/yr^2	+0.02 in/yr^2	+0.00 in/yr^2

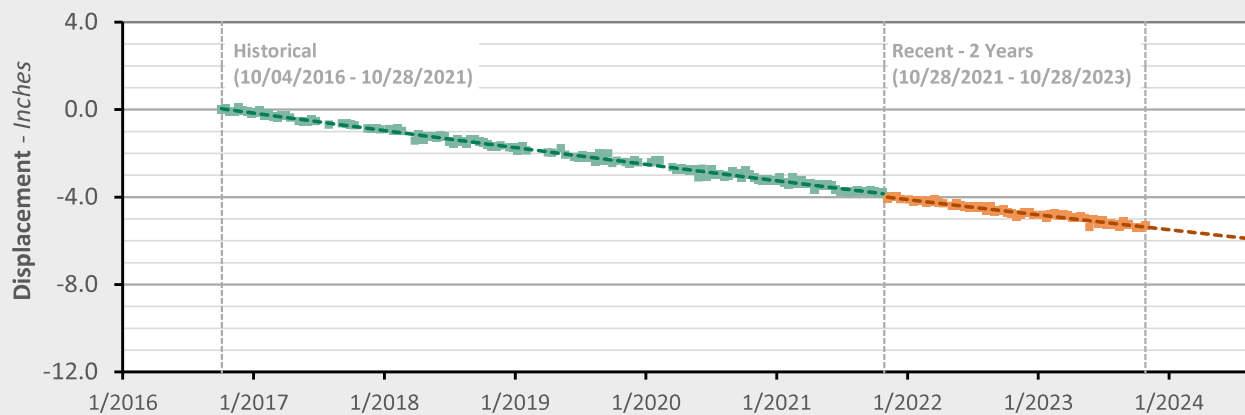|			
■ Historical LOS Displacement Measurement	– – Historical Trend Line (Quadratic Regression)	■ Recent LOS Displacement Measurement	– – Historical Trend Line (Quadratic Regression)

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AOI 5 *(PPG 21)* - Location Map

Legend:
- ☐ AOI Boundaries
- ● SNT Measurement Point
- ● TSX/PAZ Measurement Point
- — Salt Dome 500-ft Contours
- ☐ Historical Cavern Extents
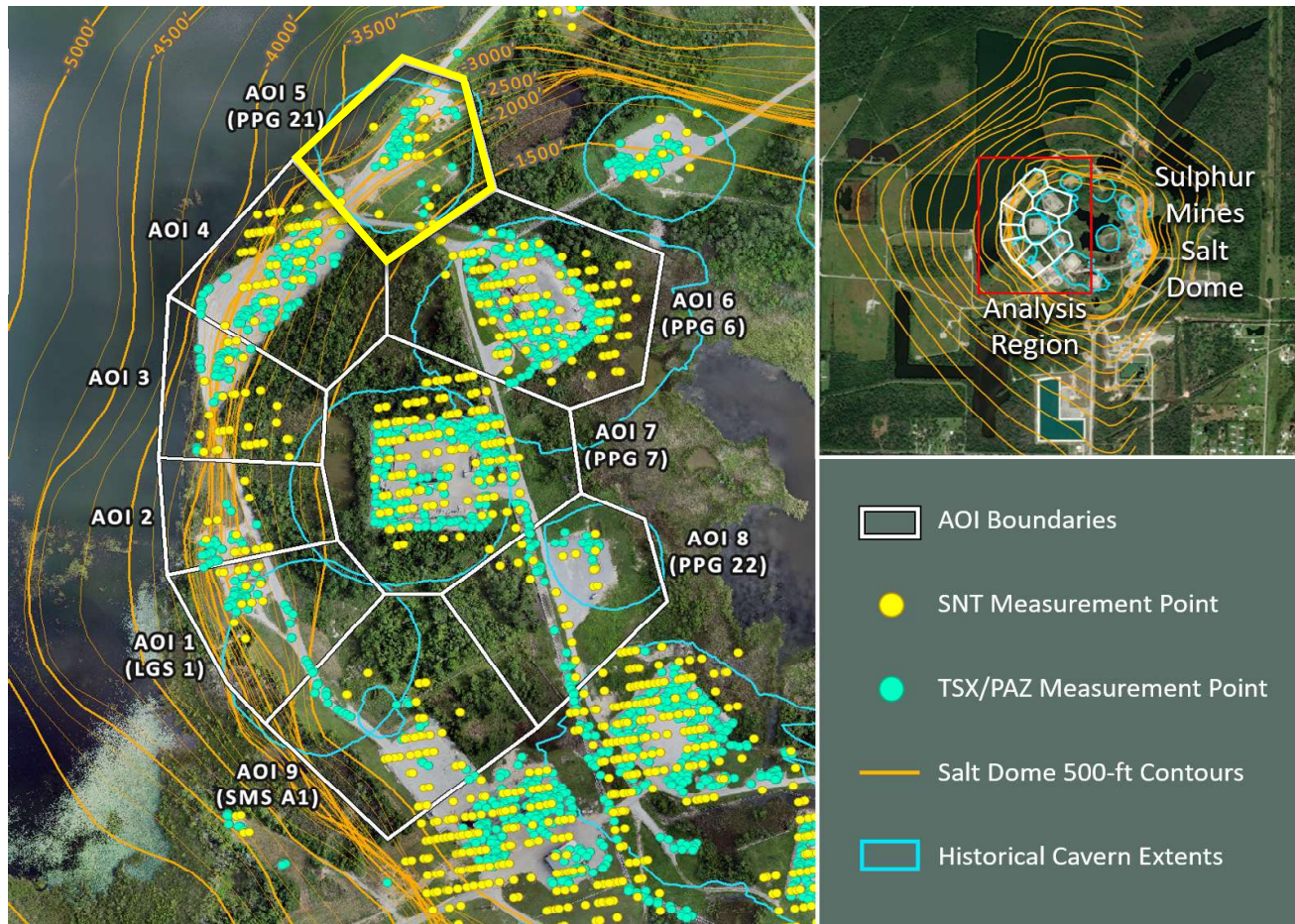
AOI 5 *(PPG 21)* - Displacement Time Series   SNT (10/28/2023) Point Count: **24**

Historical (10/04/2016 - 10/28/2021)

Recent - 2 Years (10/28/2021 - 10/28/2023)
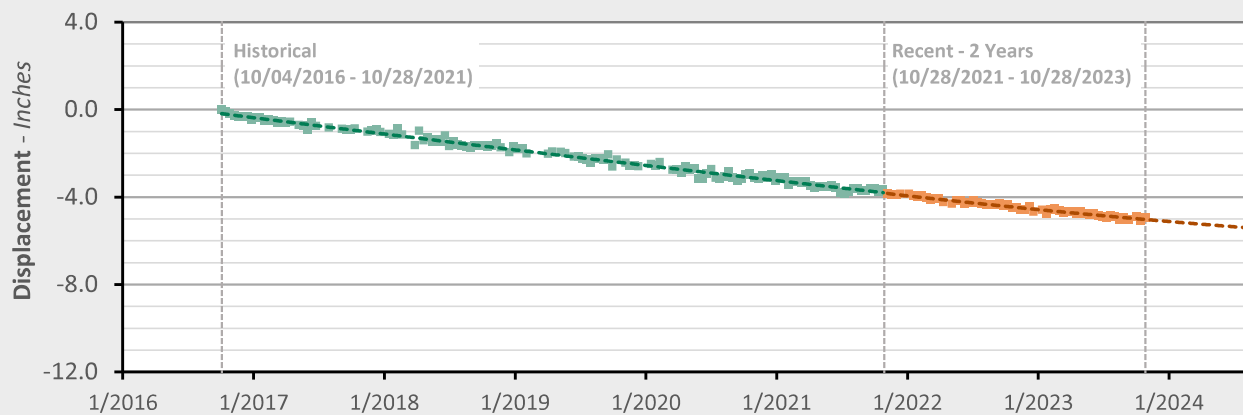
	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.67 in/yr	-0.52 in/yr	+0.15 in/yr
Acceleration:	+0.02 in/yr^2	+0.08 in/yr^2	+0.07 in/yr^2

- ■ Historical LOS Displacement Measurement
- --- Historical Trend Line (Quadratic Regression)
- ■ Recent LOS Displacement Measurement
- --- Historical Trend Line (Quadratic Regression)

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AOI 6 *(PPG 6)* - Location Map

- **AOI Boundaries**
- 🟡 **SNT Measurement Point**
- 🟢 **TSX/PAZ Measurement Point**
- **Salt Dome 500-ft Contours**
- **Historical Cavern Extents**

AOI 6 *(PPG 6)* - Displacement Time Series   SNT (10/28/2023) Point Count: **134**

	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.87 in/yr	-0.95 in/yr	-0.08 in/yr
Acceleration:	+0.06 in/yr^2	-0.04 in/yr^2	-0.10 in/yr^2

- ■ Historical LOS Displacement Measurement
- - - Historical Trend Line (Quadratic Regression)
- ■ Recent LOS Displacement Measurement
- - - Historical Trend Line (Quadratic Regression)
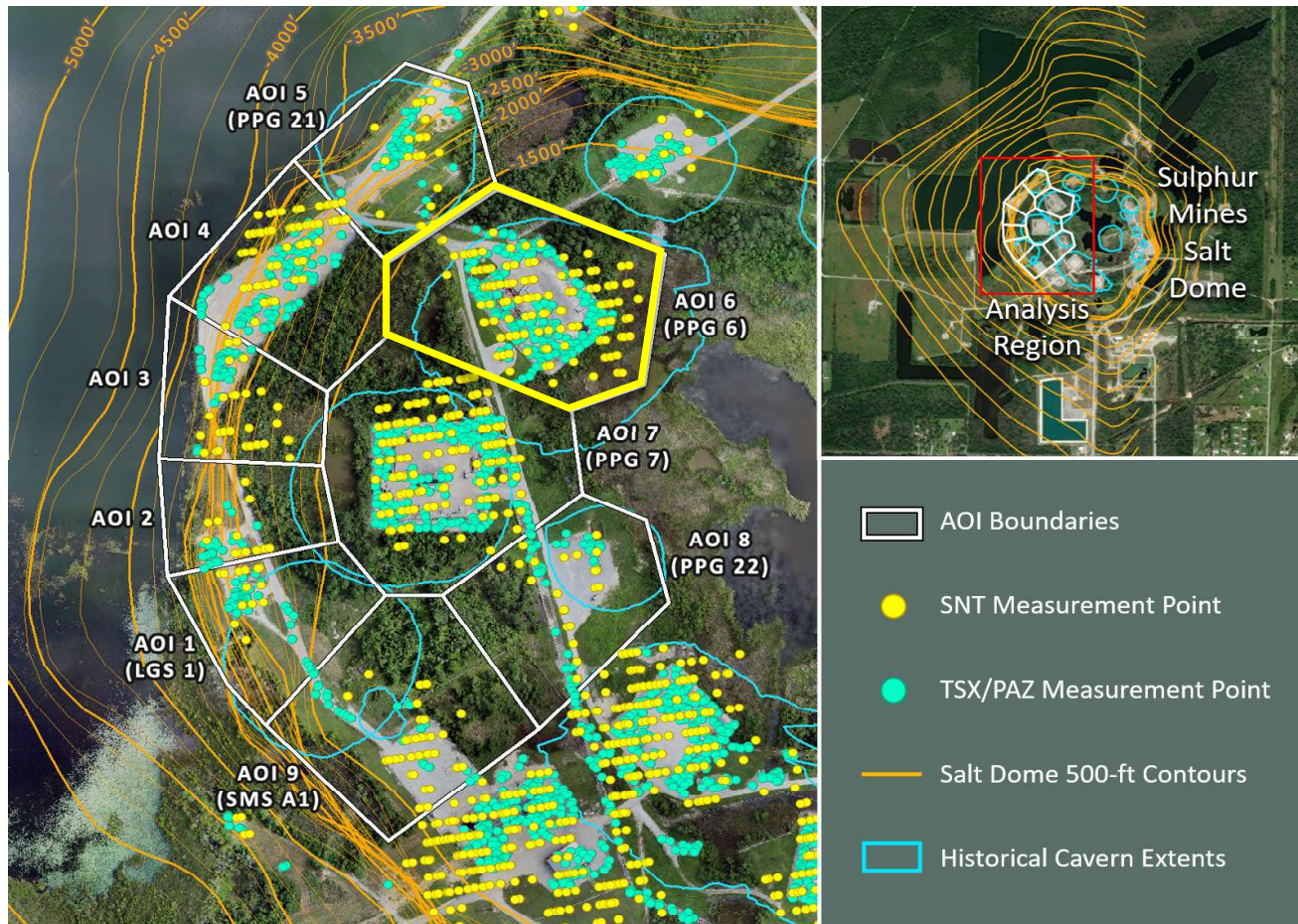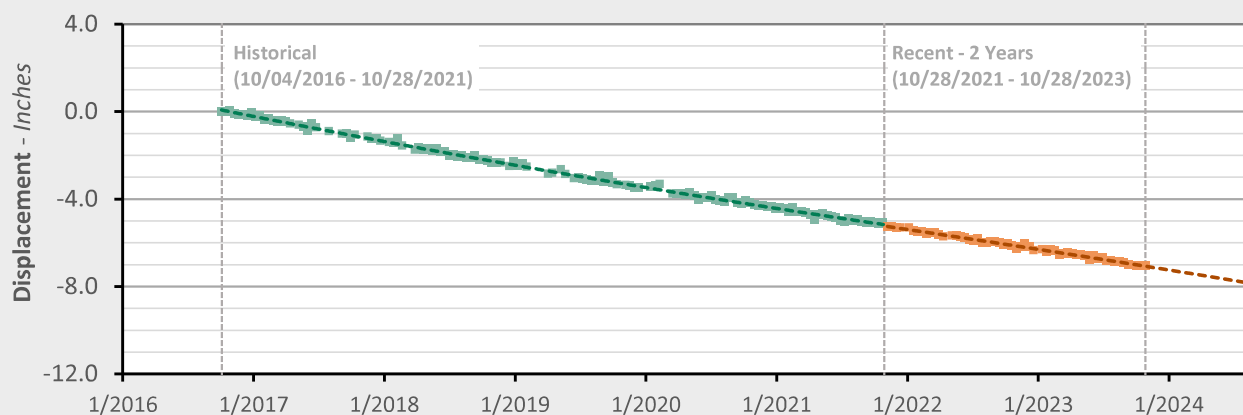
AOI 7 *(PPG 7)* - Location Map

Sulphur Mines Salt Dome

Analysis Region

AOI Boundaries

● **SNT Measurement Point**

● **TSX/PAZ Measurement Point**

— **Salt Dome 500-ft Contours**

▭ **Historical Cavern Extents**
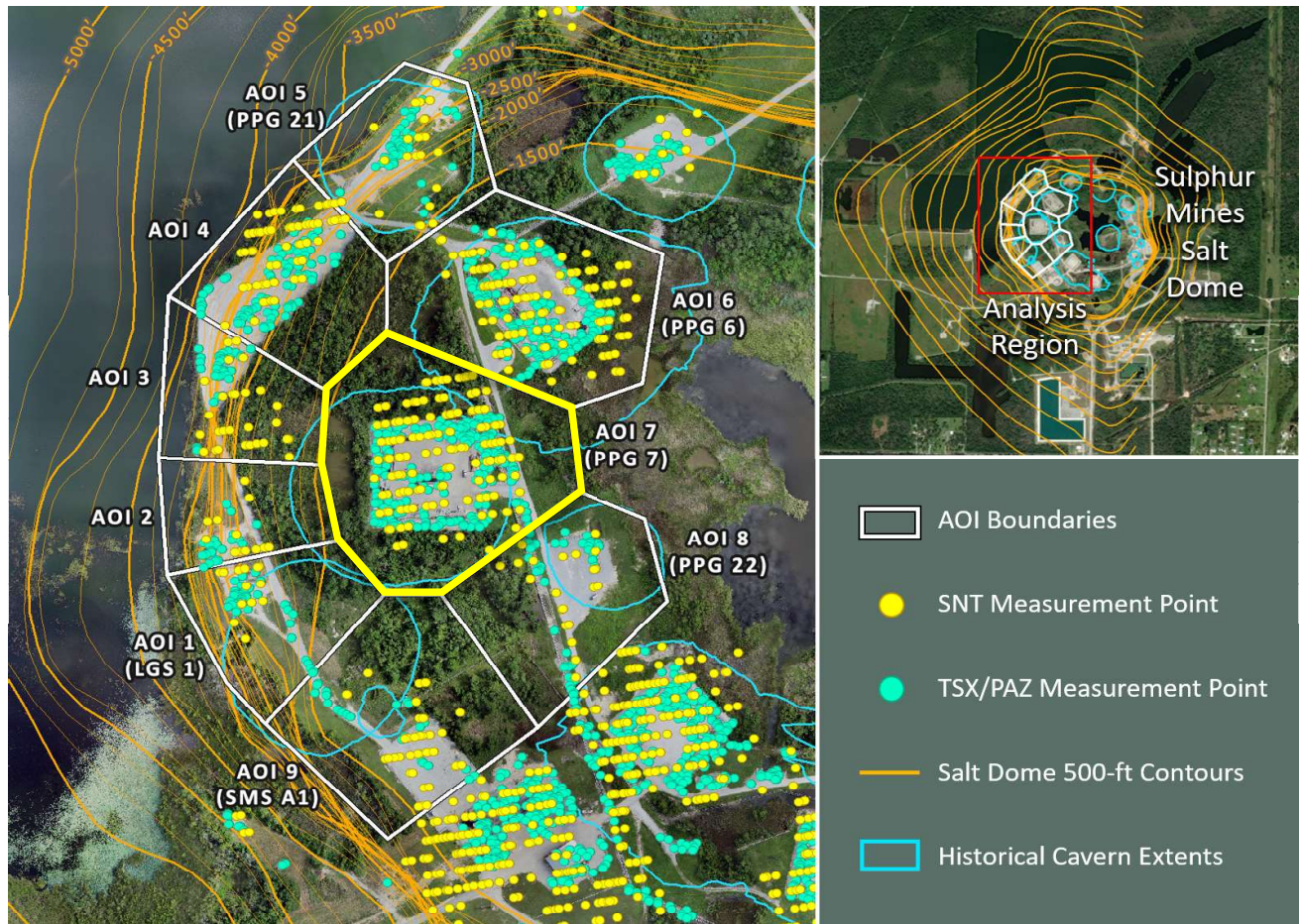
AOI 7 *(PPG 7)* - Displacement Time Series   SNT (10/28/2023) Point Count: **140**

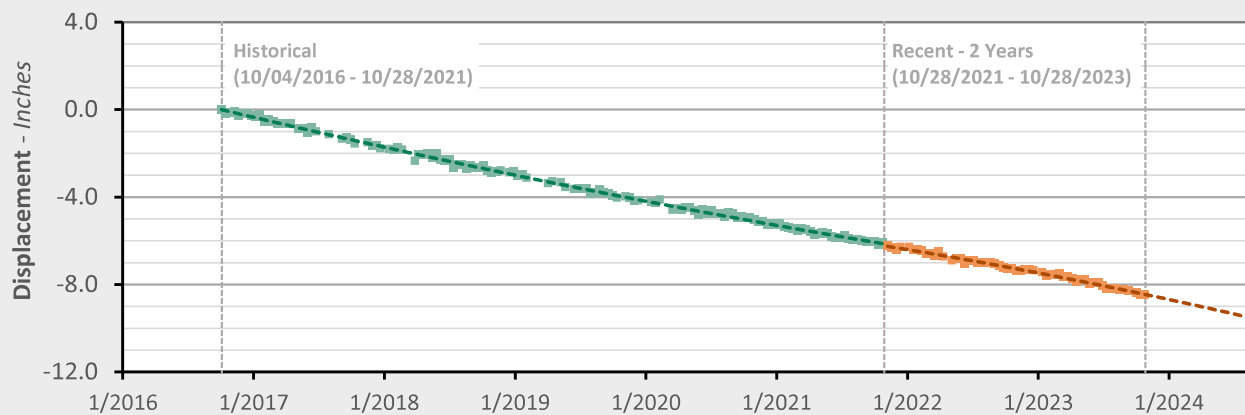|	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.99 in/yr	-1.26 in/yr	-0.27 in/yr
Acceleration:	+0.09 in/yr^2	-0.15 in/yr^2	-0.24 in/yr^2

■ Historical LOS Displacement Measurement   - - - Historical Trend Line (Quadratic Regression)   ■ Recent LOS Displacement Measurement   - - - Historical Trend Line (Quadratic Regression)

AOI 8 *(PPG 22)* - Location Map

Sulphur
Mines
Salt
Dome

Analysis
Region

AOI Boundaries

● **SNT Measurement Point**

● **TSX/PAZ Measurement Point**

— **Salt Dome 500-ft Contours**

▭ **Historical Cavern Extents**

AOI 5
(PPG 21)

AOI 4

AOI 3

AOI 2

AOI 1
(LGS 1)

AOI 9
(SMS A1)

AOI 6
(PPG 6)

AOI 7
(PPG 7)
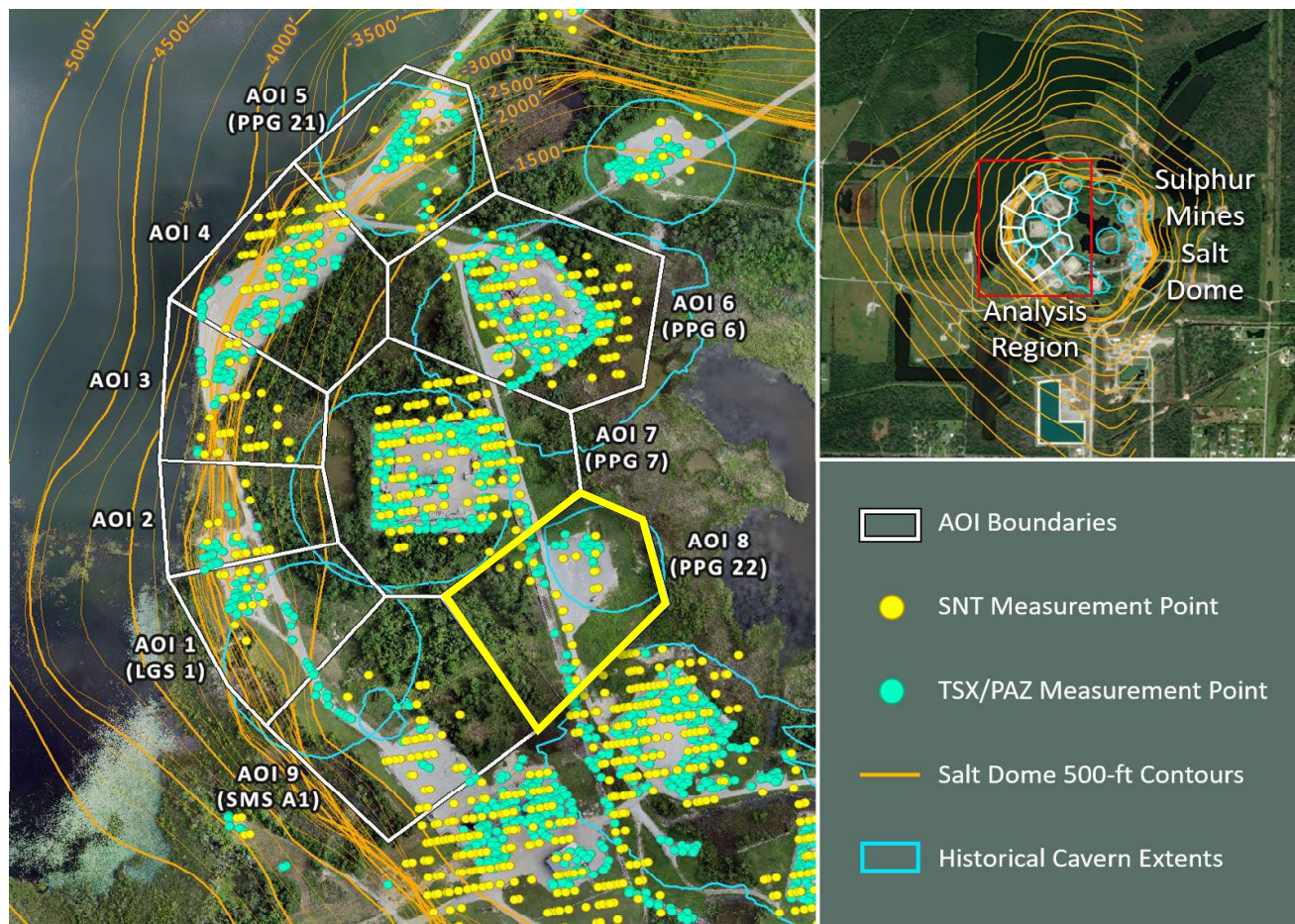
AOI 8
(PPG 22)

AOI 8 *(PPG 22)* - Displacement Time Series   SNT (10/28/2023) Point Count: **21**

Historical
(10/04/2016 - 10/28/2021)

Recent - 2 Years
(10/28/2021 - 10/28/2023)
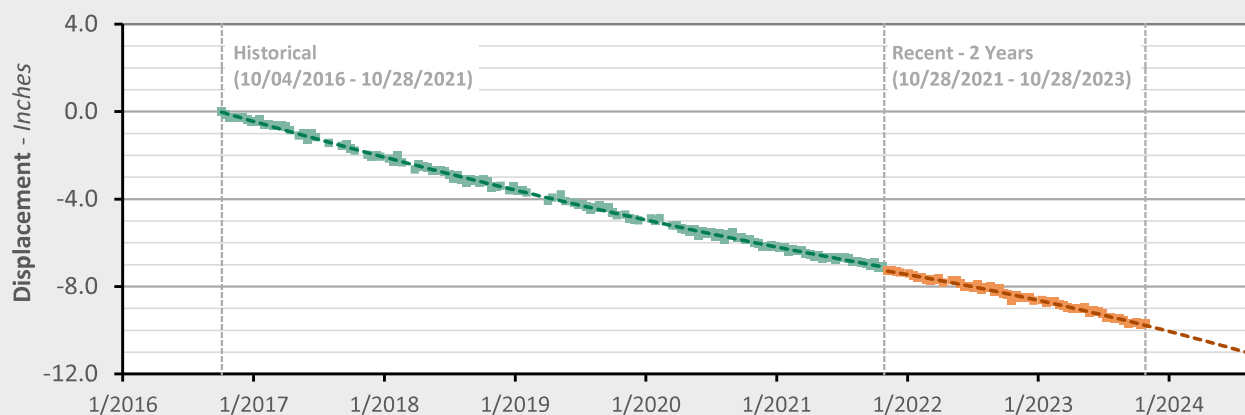
	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-1.06 in/yr	-1.50 in/yr	-0.44 in/yr
Acceleration:	+0.13 in/yr^2	-0.25 in/yr^2	-0.38 in/yr^2

■ Historical LOS Displacement Measurement

╌ Historical Trend Line (Quadratic Regression)

■ Recent LOS Displacement Measurement

╌ Historical Trend Line (Quadratic Regression)
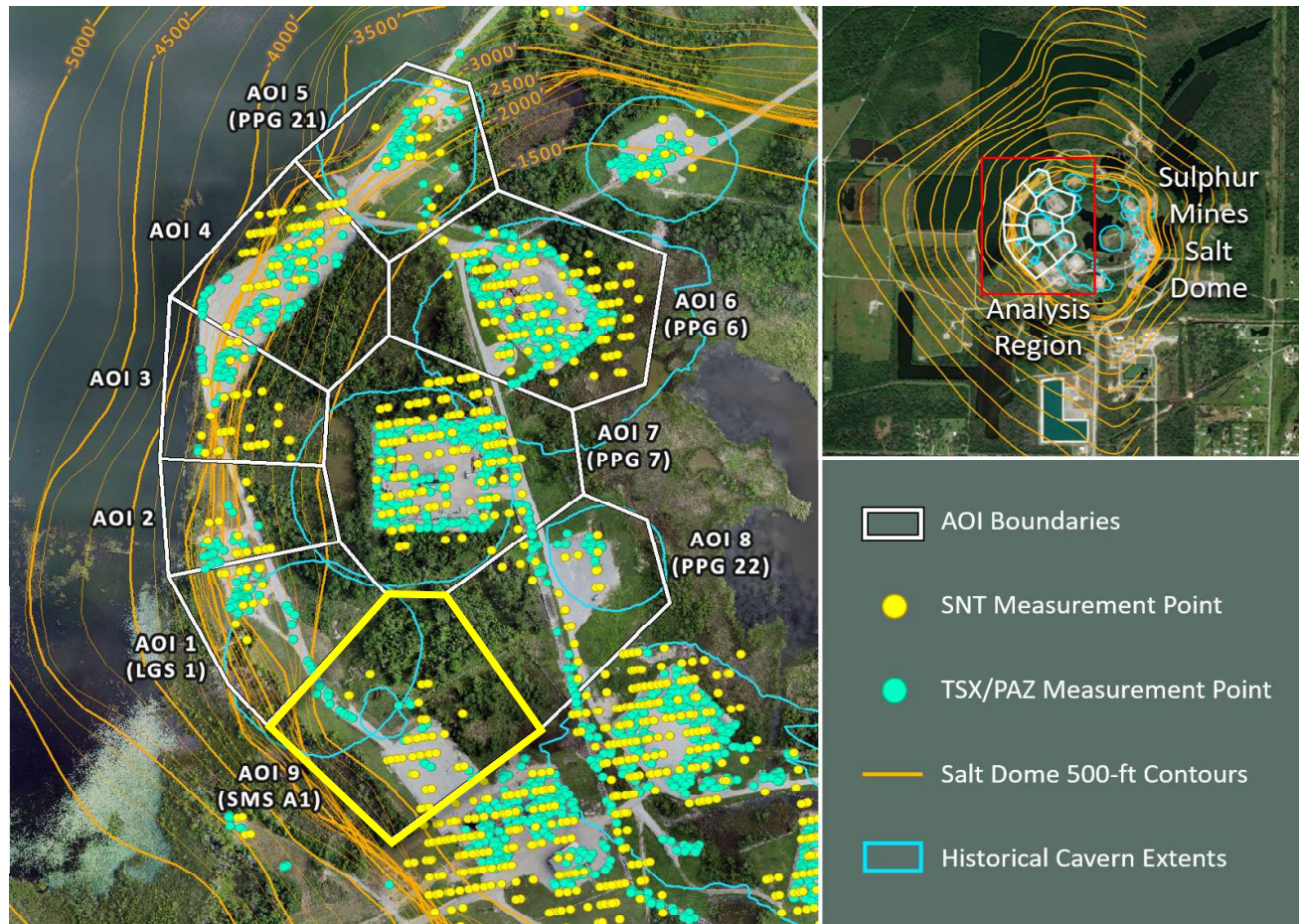
AOI 9 *(PPG A1)* - Location Map

Sulphur Mines Salt Dome

Analysis Region

Legend:
- AOI Boundaries
- SNT Measurement Point (yellow)
- TSX/PAZ Measurement Point (teal)
- Salt Dome 500-ft Contours
- Historical Cavern Extents

AOI 9 *(SMS A1)* - Displacement Time Series   SNT (10/28/2023) Point Count: **39**
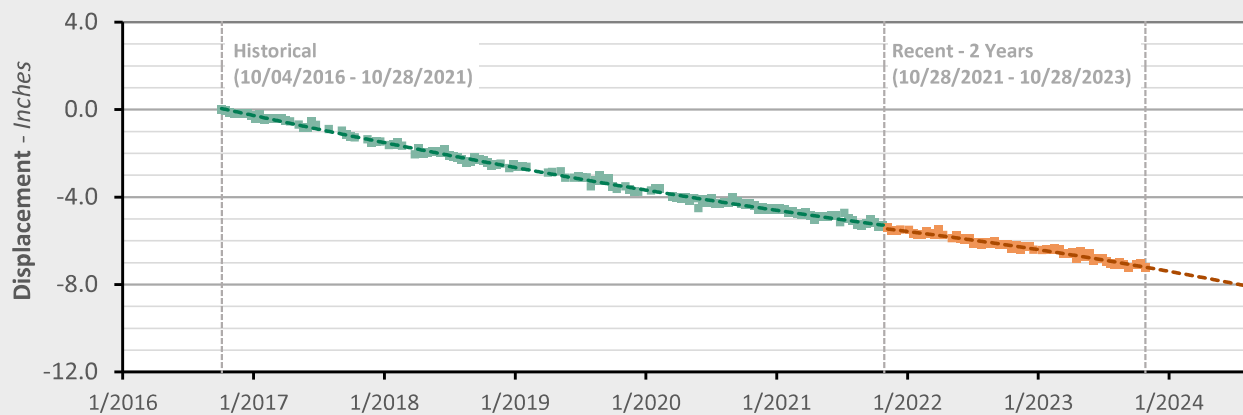
	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.79 in/yr	-1.04 in/yr	-0.26 in/yr
Acceleration:	+0.10 in/yr^2	-0.16 in/yr^2	-0.27 in/yr^2

Legend:
- Historical LOS Displacement Measurement
- Historical Trend Line (Quadratic Regression)
- Recent LOS Displacement Measurement
- Historical Trend Line (Quadratic Regression)

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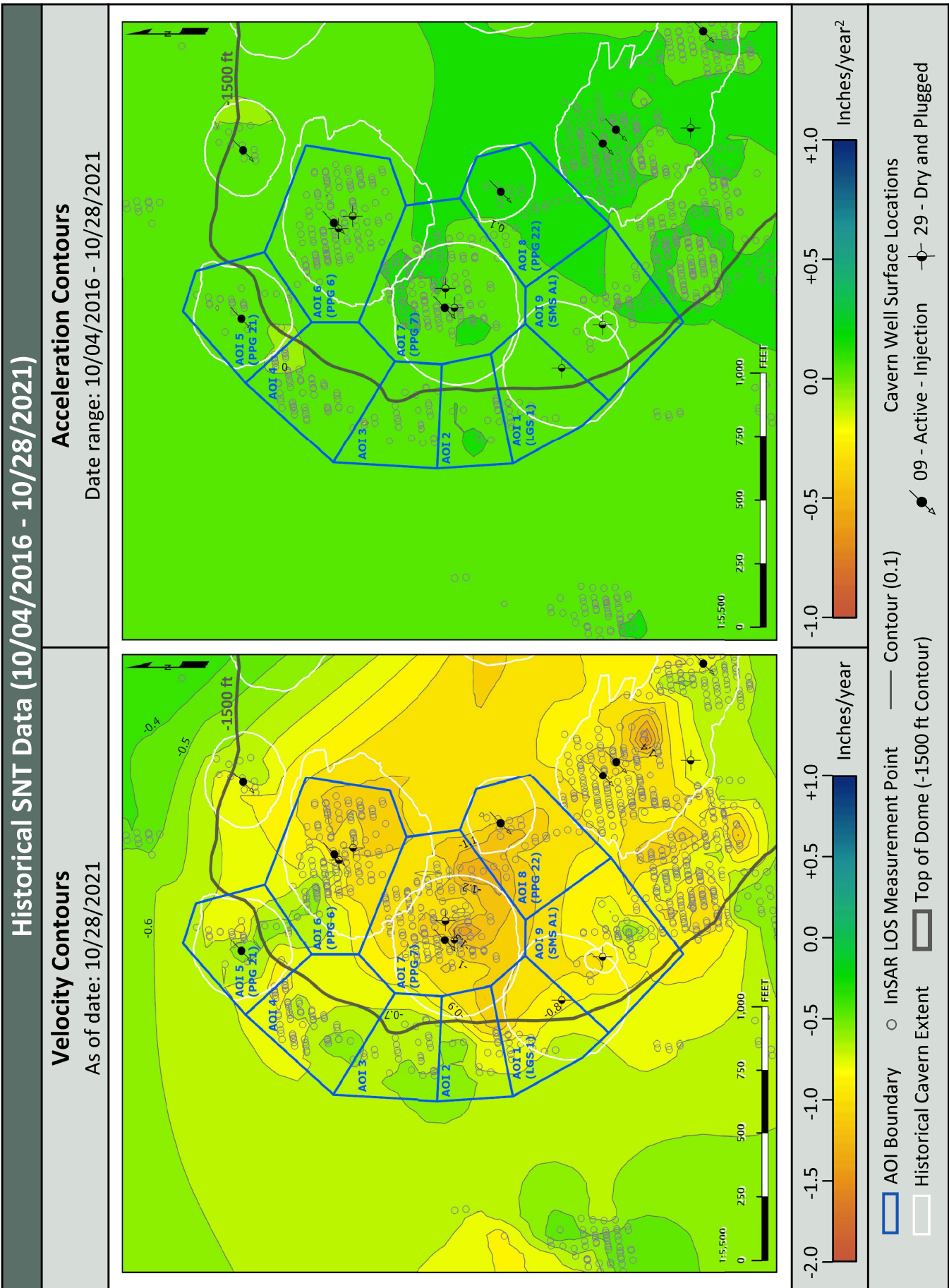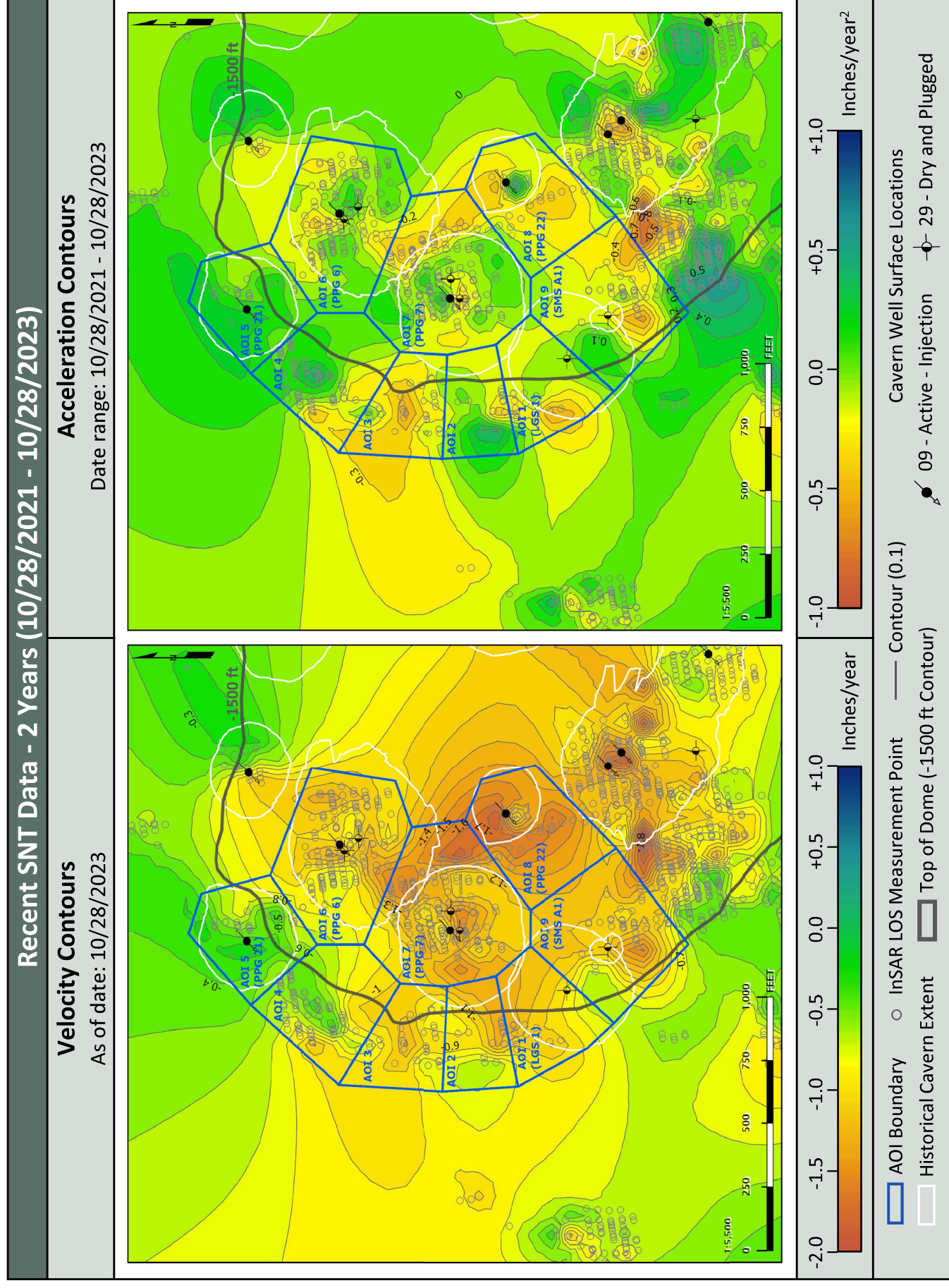LOS Displacement Velocity and Acceleration Maps

Historical SNT Data (10/04/2016 - 10/28/2021)

Velocity Contours
As of date: 10/28/2021

Acceleration Contours
Date range: 10/04/2016 - 10/28/2021

Dataset: SNT (10-28-2023).xlsx

Analysis Date: 11/1/2023

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LOS Displacement Velocity and Acceleration Maps

Recent SNT Data - 2 Years (10/28/2021 - 10/28/2023)

Velocity Contours
As of date: 10/28/2023

Acceleration Contours
Date range: 10/28/2021 - 10/28/2023

Dataset: SNT (10-28-2023).xlsx

Analysis Date: 11/1/2023

LOS Displacement Velocity and Acceleration Maps

Change from Historical to Recent SNT Data

Velocity Contours

Historical Velocity subtracted from Recent Velocity

Acceleration Contours

Historical Acceleration subtracted from Recent Acceleration

Inches/year

Inches/year^2

AOI Boundary   InSAR LOS Measurement Point   Contour (0.1)   Cavern Well Surface Locations

Historical Cavern Extent   Top of Dome (-1500 ft Contour)   09 - Active - Injection   29 - Dry and Plugged

Dataset: SNT (10-28-2023).xlsx

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Analysis Date: 11/1/2023