Westlake US 2
Received 8/23/2023

**SNT Satellite Update**
**InSAR Subsidence**
August 17, 2023

Longuist comment:

"The SNT satellite (12-day revisit) passed by Sulphur on Thursday August 17. We noted the delivery of the dataset was delayed by a few days and we will plan to inquire with TREA on the cause if we see this again. When we received the dataset Monday we 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:
Lonquist & Co., LLC
8591 United Plaza Blvd., Suite 280
Baton Rouge, LA 70809

| Dataset |
| --- |
| Satellite Source |
| **Sentinel-1 (SNT)** |
| Most Recent Image Date |
| **Thursday, August 17, 2023** |

Analysis Report Date:

**August 23, 2023**

## Dataset Information

| | |
|---|---|
| Satellite Source | Sentinel-1 (SNT) |
| Revisit Frequency | 12 days |
| Most Recent Image Date | Thursday, August 17, 2023 |
| Dataset Image Count | 185 |
| Dataset Time Range | October 4, 2016 - August 17, 2023 |
| Dataset Length | 6.87 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**

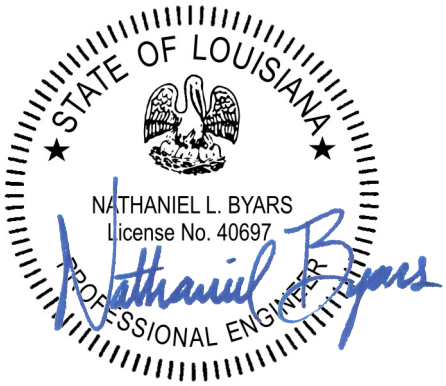
The multi-year SNT dataset timeframe allows for Recent data to be evaluated separately from Historical data and for trends from the two timeframes to be compared. The change in the velocities and accelerations from the two timeframes are provided in the Time Series and Contour Map sections. Velocity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

## Observations

To-date there has been no material deviation 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 of LOS displacement in AOI 1 and AOI 2 and as well as a minor increase in negative velocity and negative acceleration in AOI 3, 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.

Mapped contours of the change in recent vs. historical subsidence rates mostly show minor fluctuations around 0, intermittently distributed within the AOIs. This suggests that statistically relevant areas of change may not yet be apparent outside of the confidence range associated with the trend




Date Signed: August 23, 2023
Austin, Texas

Nathaniel L. Byars, P.E.
Principal Engineer Louisiana
License No. 40697

## InSAR Data Sources

**InSAR Data**

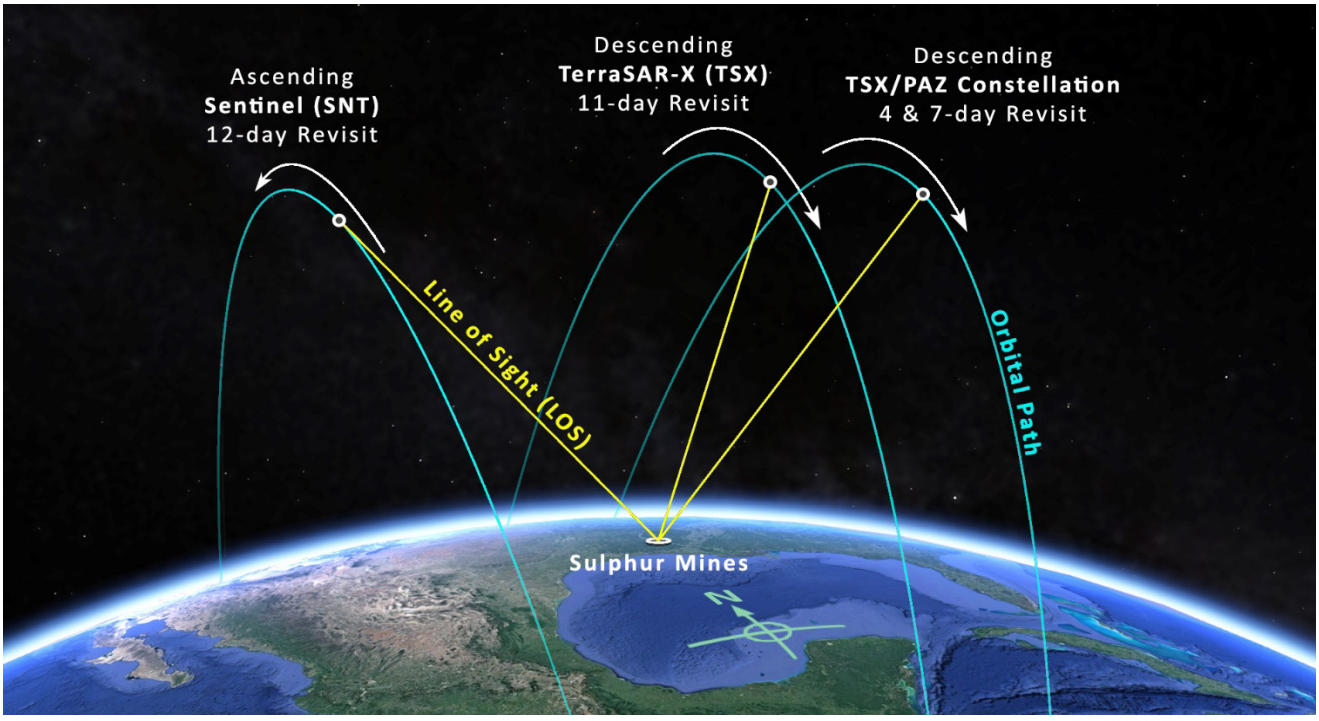
Interferometric Synthetic Aperture Radar (InSAR) is the most well established method to continually evaluate small, normally undetectable, ground movement over a large area. Radar imagery collected via satellites over successive orbital passes is used to identify and define measurement points on the 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) displacment 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.

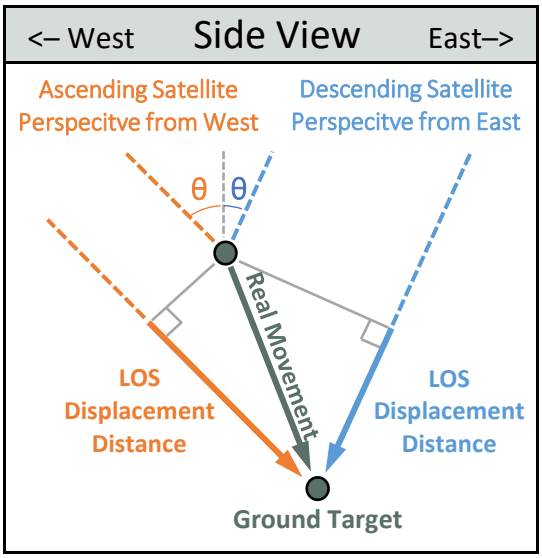
The first dataset comes from a low-resolution Sentinel-1 (SNT) satellite on an ascending orbit that captures data from the west of the site on a 12-day frequency. The second comes from a high-resolution TerraSAR-X (TSX) satellite on a descending orbit that captures data from the east of the site on an 11-day frequency. This dataset will be replaced in May 2023 by data from a pair of high resolution satellites that share the same descending orbit. These are a second 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. This transition is being made for the increased data frequency that will result 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

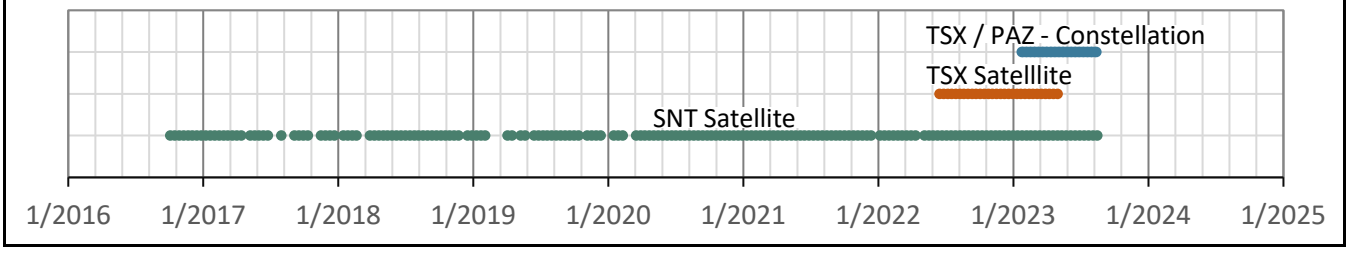
LOS displacement measurements refer to a change in distance between the satellite sensor and the ground target. Measurement positions on the west side of the Sulphur Dome are are known to be experiencing some eastward movement toward the dome center due to the geometry of the subsidence basin. The InSAR 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.



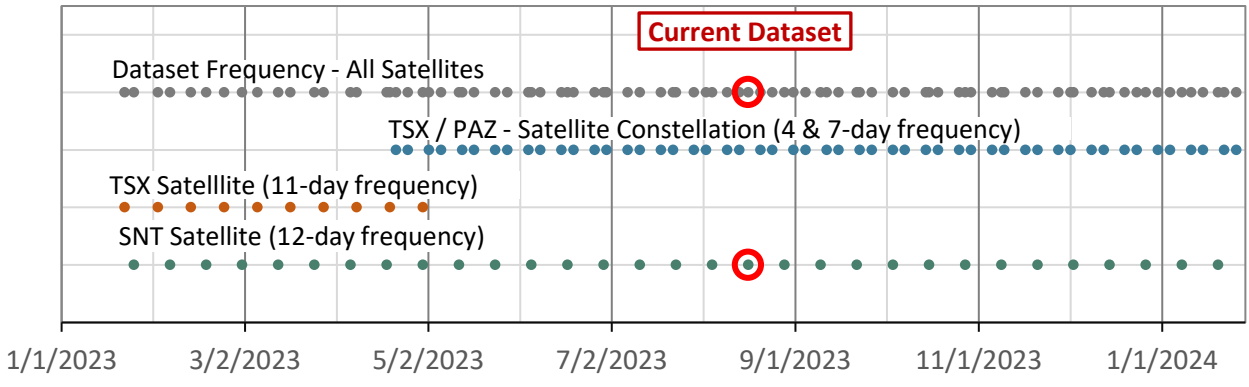

## Satellite Properties & Image Frequency

| 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, $\theta$)** | 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 |

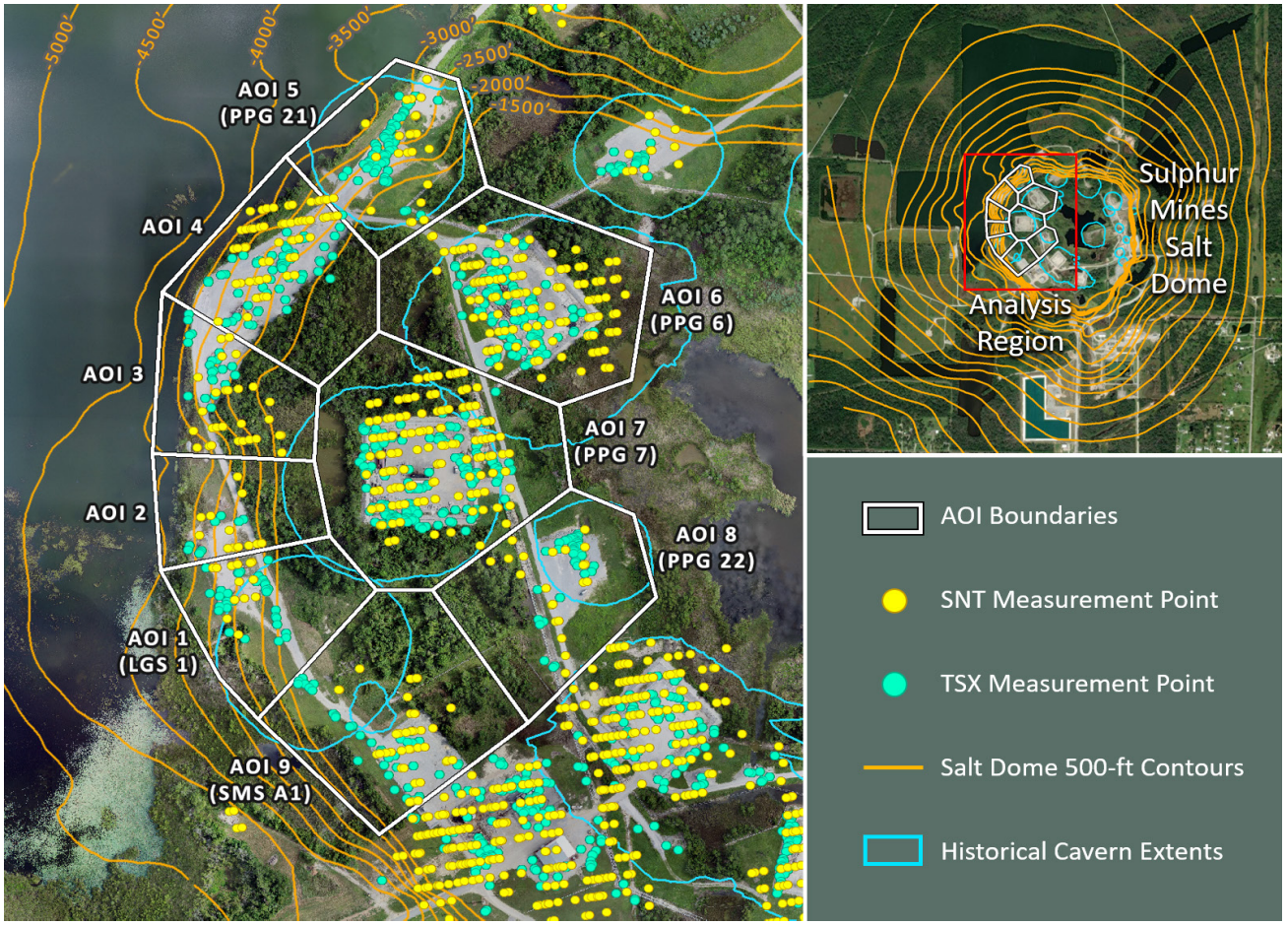
### Dataset Measurement History




### Dataset Update Frequency



## AOI Boundaries & InSAR Measurement Points

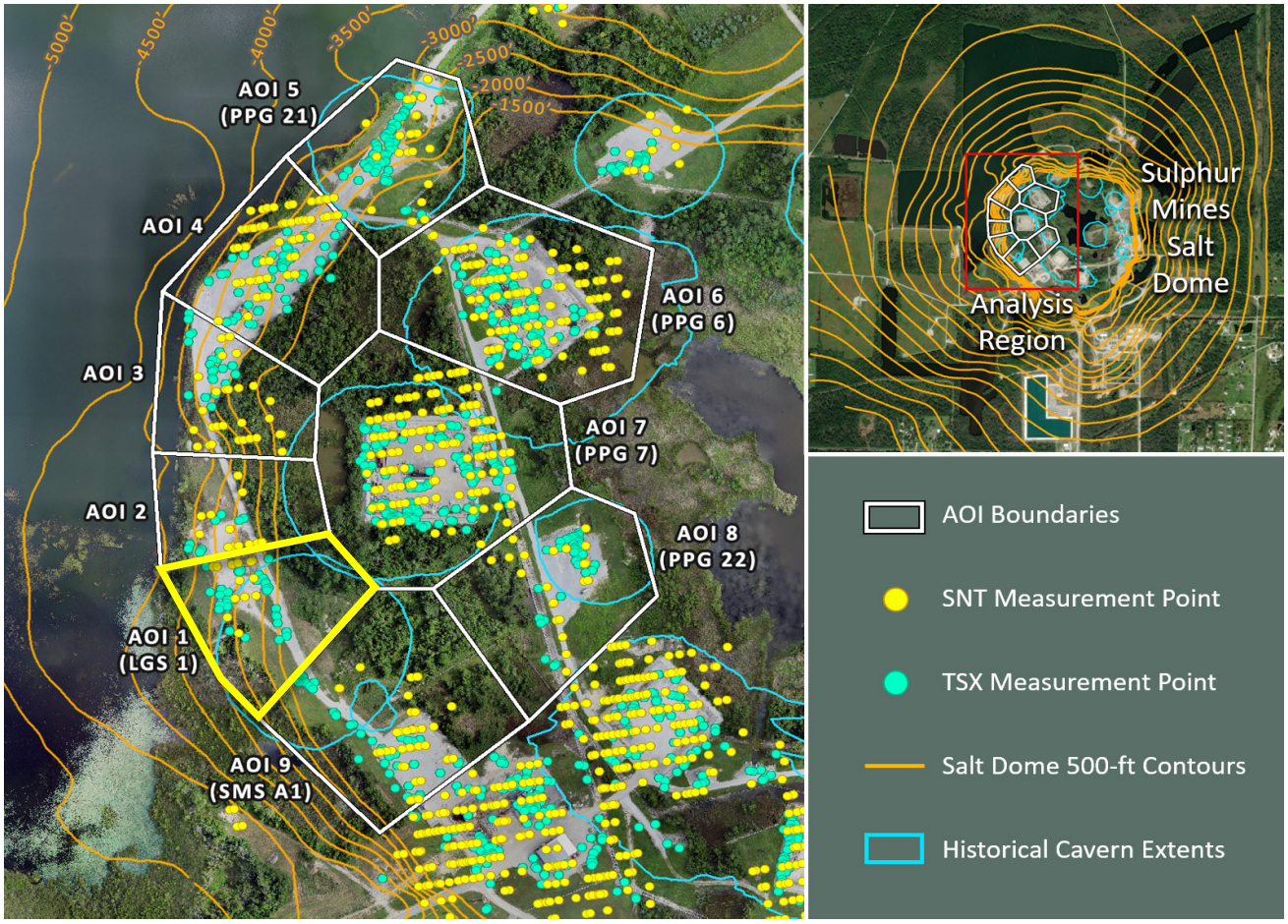



## Subsidence Monitoring Areas of Interest (AOIs)

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.

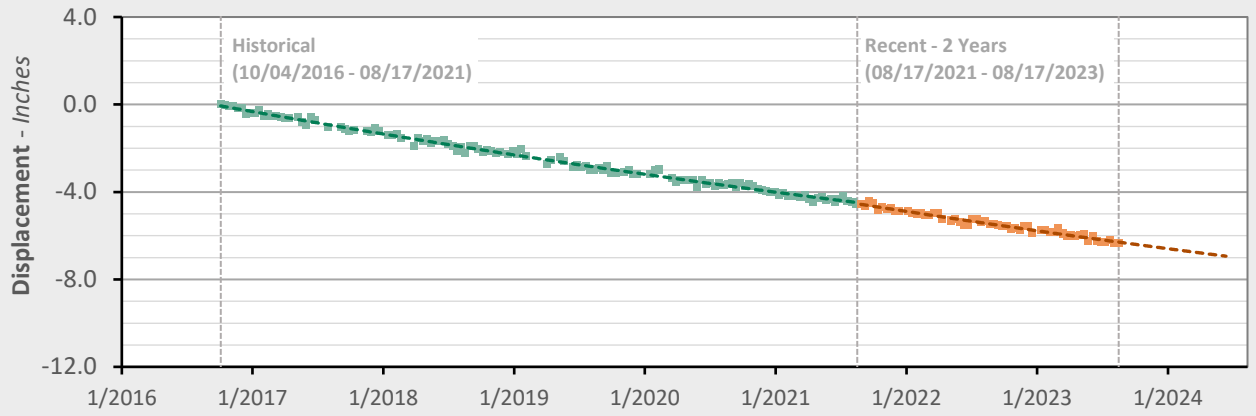
| AOI Name | SNT (8/17/2023) | LOS Velocity *(in/yr)* | | | LOS Acceleration *(in/yr$^2$)* | | |
|---|---|---|---|---|---|---|---|
| | Point Count | Historical | Recent | Change | Historical | Recent | Change |
| **AOI 1** *(LGS 1)* | 13 | -0.74 | -0.81 | -0.07 | +0.07 | +0.07 | -0.00 |
| **AOI 2** | 15 | -0.68 | -0.81 | -0.12 | +0.11 | +0.14 | +0.03 |
| **AOI 3** | 29 | -0.67 | -0.74 | -0.07 | +0.03 | -0.04 | -0.07 |
| **AOI 4** | 62 | -0.73 | -0.63 | +0.10 | +0.02 | +0.13 | +0.12 |
| **AOI 5** *(PPG 21)* | 25 | -0.71 | -0.54 | +0.17 | +0.00 | +0.12 | +0.11 |
| **AOI 6** *(PPG 6)* | 134 | -0.88 | -0.90 | -0.01 | +0.06 | +0.04 | -0.02 |
| **AOI 7** *(PPG 7)* | 140 | -1.00 | -1.15 | -0.15 | +0.09 | -0.04 | -0.13 |
| **AOI 8** *(PPG 22)* | 21 | -1.08 | -1.30 | -0.21 | +0.14 | -0.03 | -0.17 |
| **AOI 9** *(SMS A1)* | 39 | -0.78 | -0.91 | -0.14 | +0.11 | -0.02 | -0.14 |

## AOI 1 *(LGS 1)* - Location Map




## AOI 1 *(LGS 1)* - Displacement Time Series

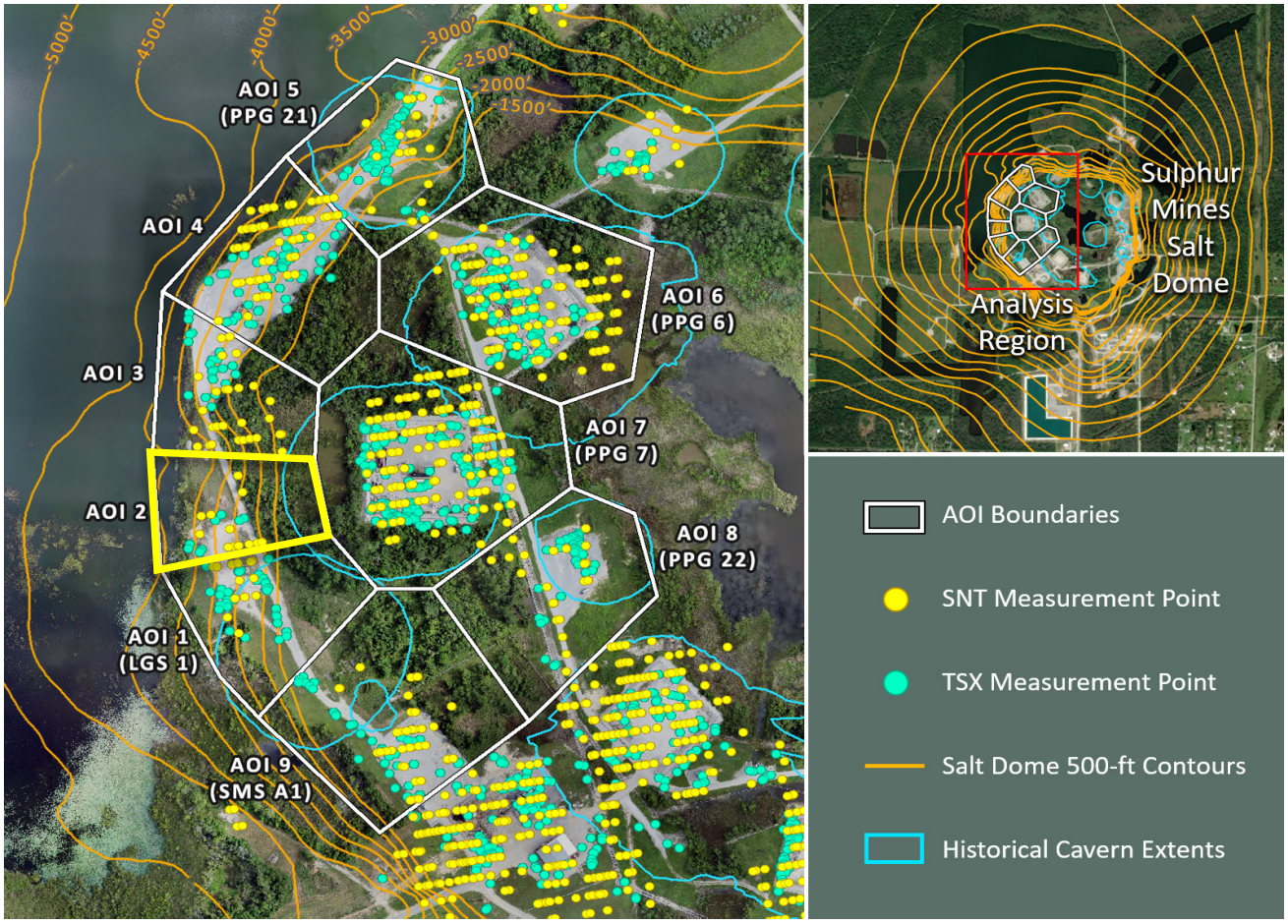
SNT (8/17/2023) Point Count: **13**




| | Historical Trend Values | Recent Trend Values | Trend Change |
|---|---|---|---|
| Velocity: | -0.74 in/yr | -0.81 in/yr | -0.07 in/yr |
| Acceleration: | +0.07 in/yr$^2$ | +0.07 in/yr$^2$ | -0.00 in/yr$^2$ |

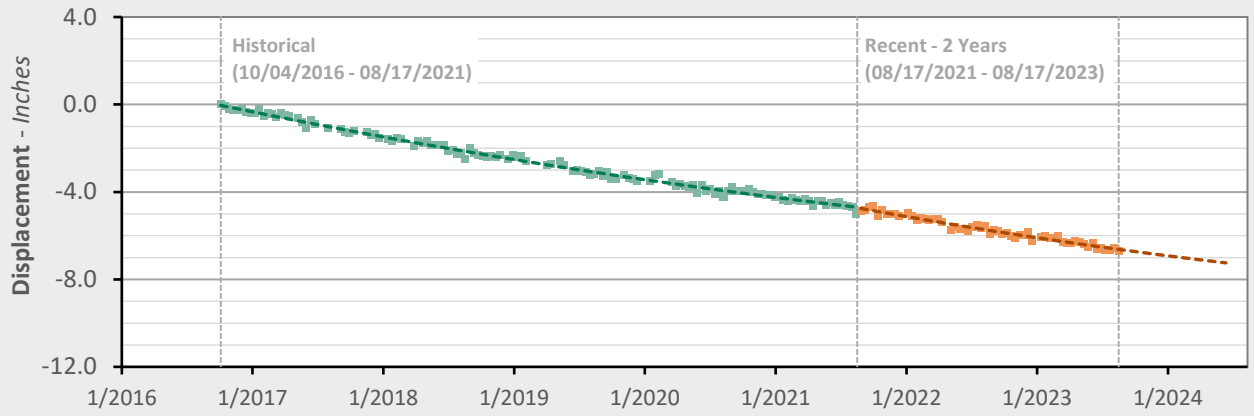
Historical LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)
Recent LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)

## AOI 2 - Location Map




## AOI 2 - Displacement Time Series

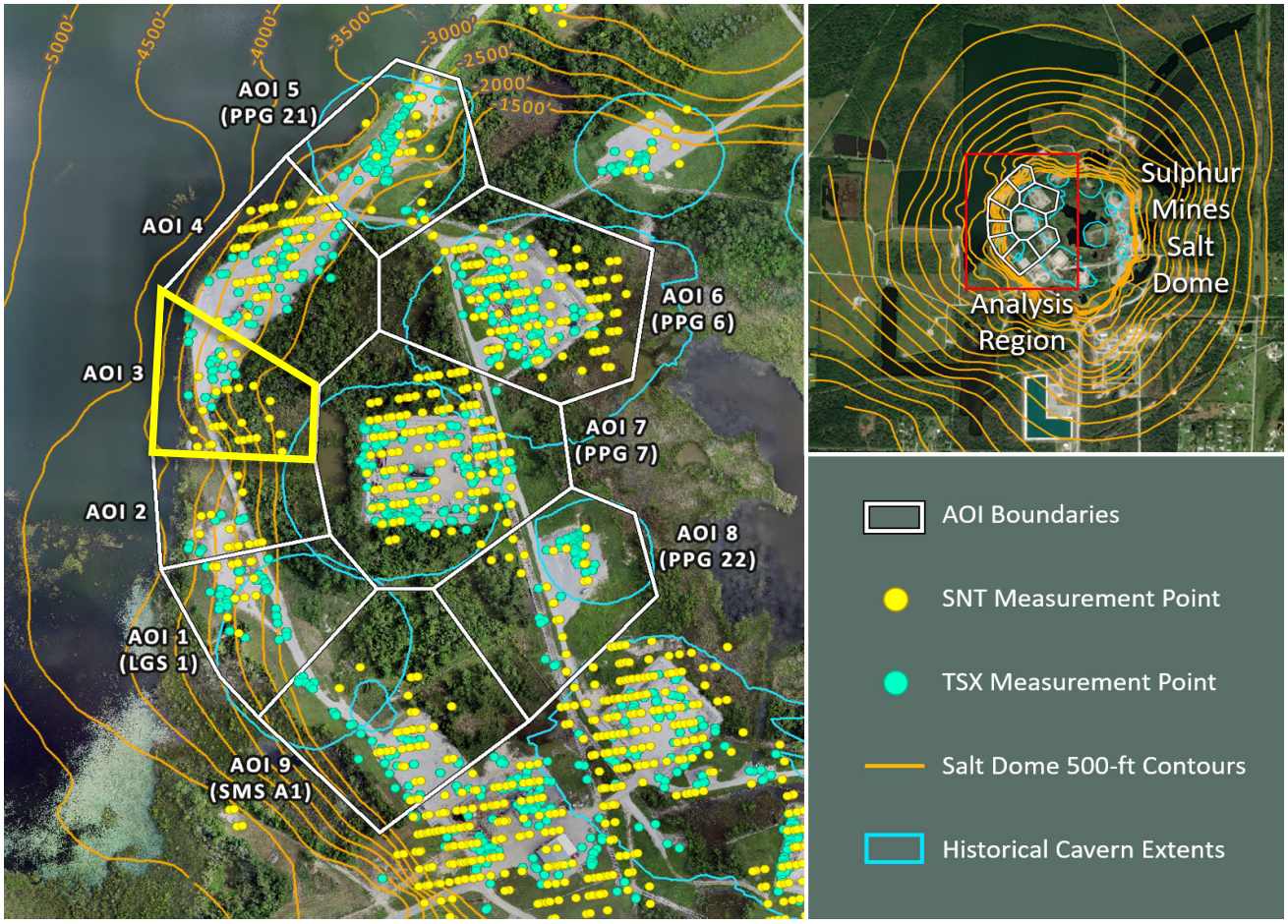
SNT (8/17/2023) Point Count: **15**




| | Historical Trend Values | Recent Trend Values | Trend Change |
|---|---|---|---|
| Velocity: | -0.68 in/yr | -0.81 in/yr | -0.12 in/yr |
| Acceleration: | +0.11 in/yr$^2$ | +0.14 in/yr$^2$ | +0.03 in/yr$^2$ |

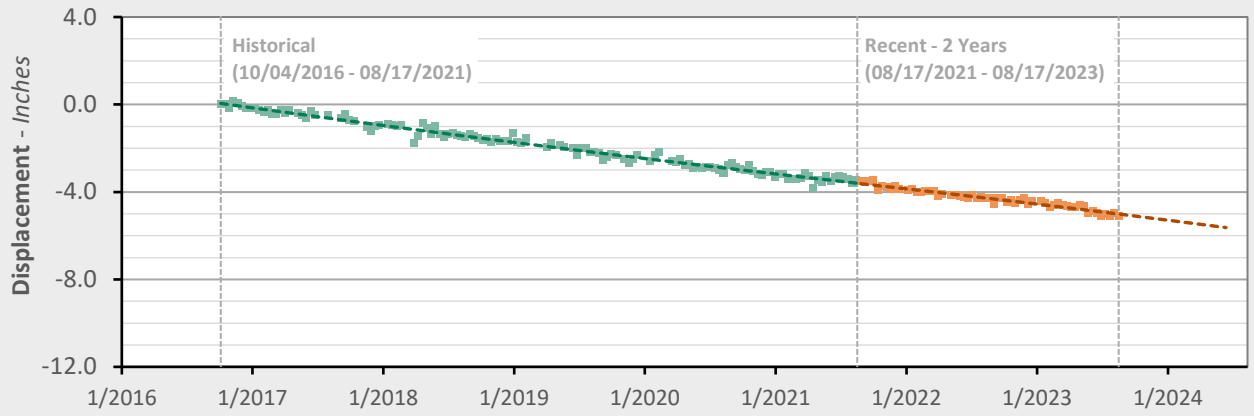
Historical LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)
Recent LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)

## AOI 3 - Location Map




## AOI 3 - Displacement Time Series

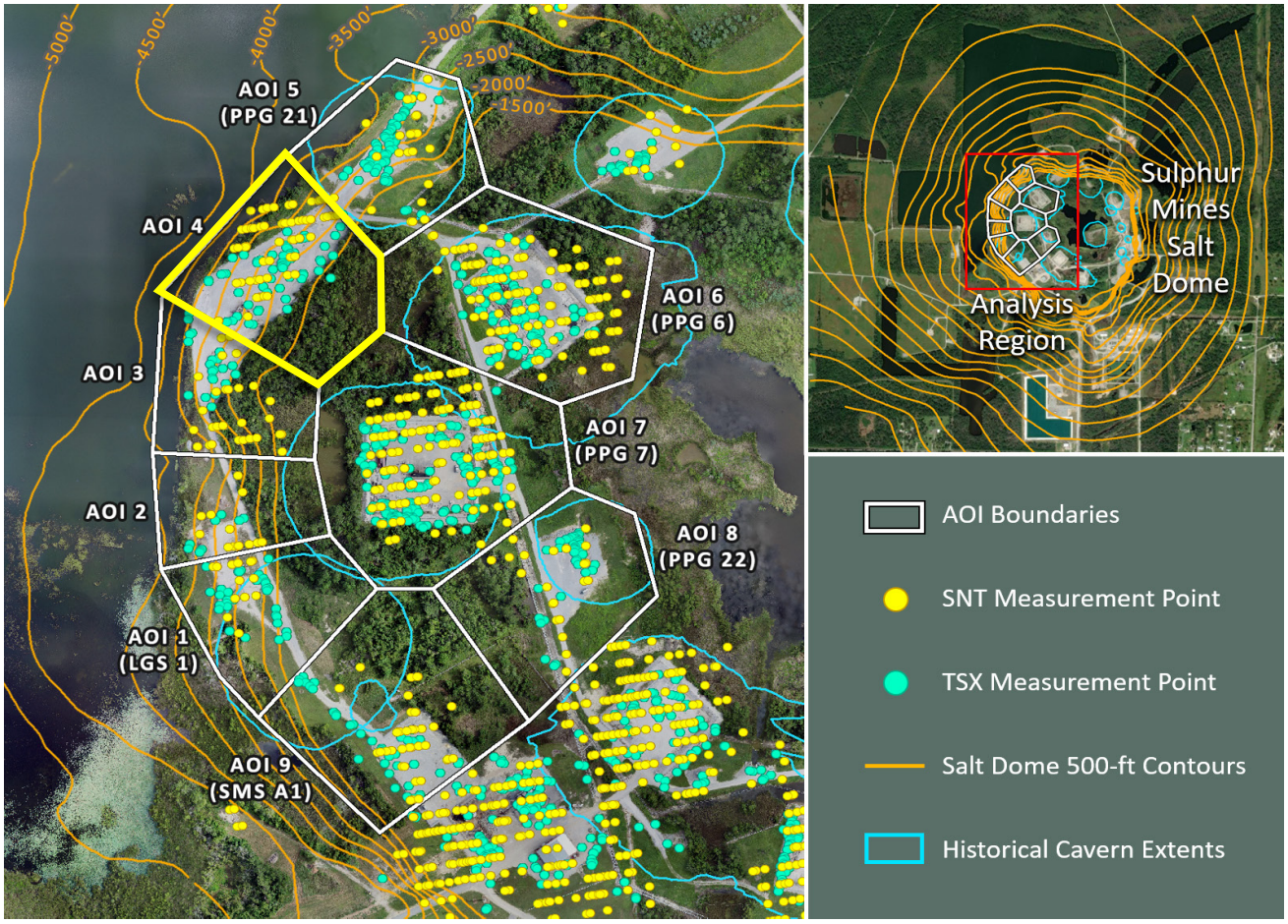
SNT (8/17/2023) Point Count: **29**




| | Historical Trend Values | Recent Trend Values | Trend Change |
|---|---|---|---|
| Velocity: | -0.67 in/yr | -0.74 in/yr | -0.07 in/yr |
| Acceleration: | +0.03 in/yr$^2$ | -0.04 in/yr$^2$ | -0.07 in/yr$^2$ |

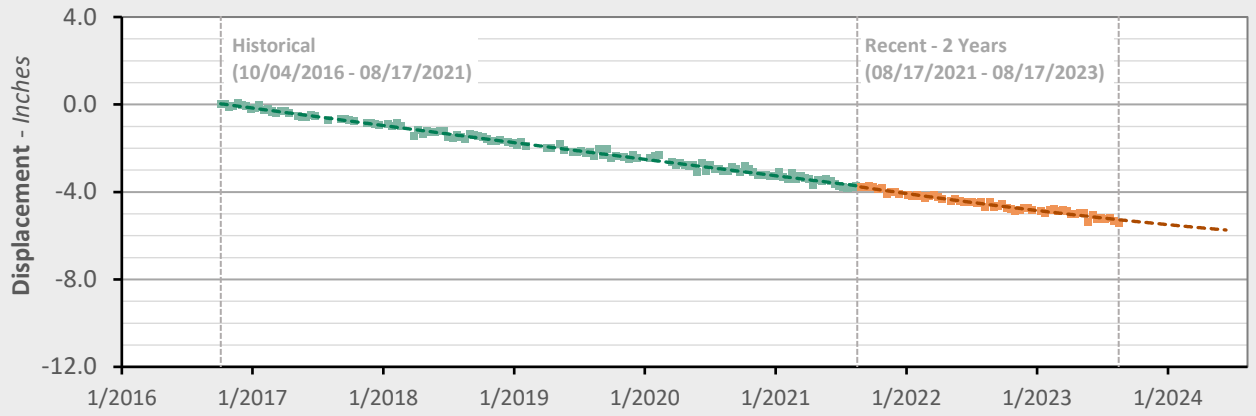
Historical LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)
Recent LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)

## AOI 4 - Location Map




## AOI 4 - Displacement Time Series

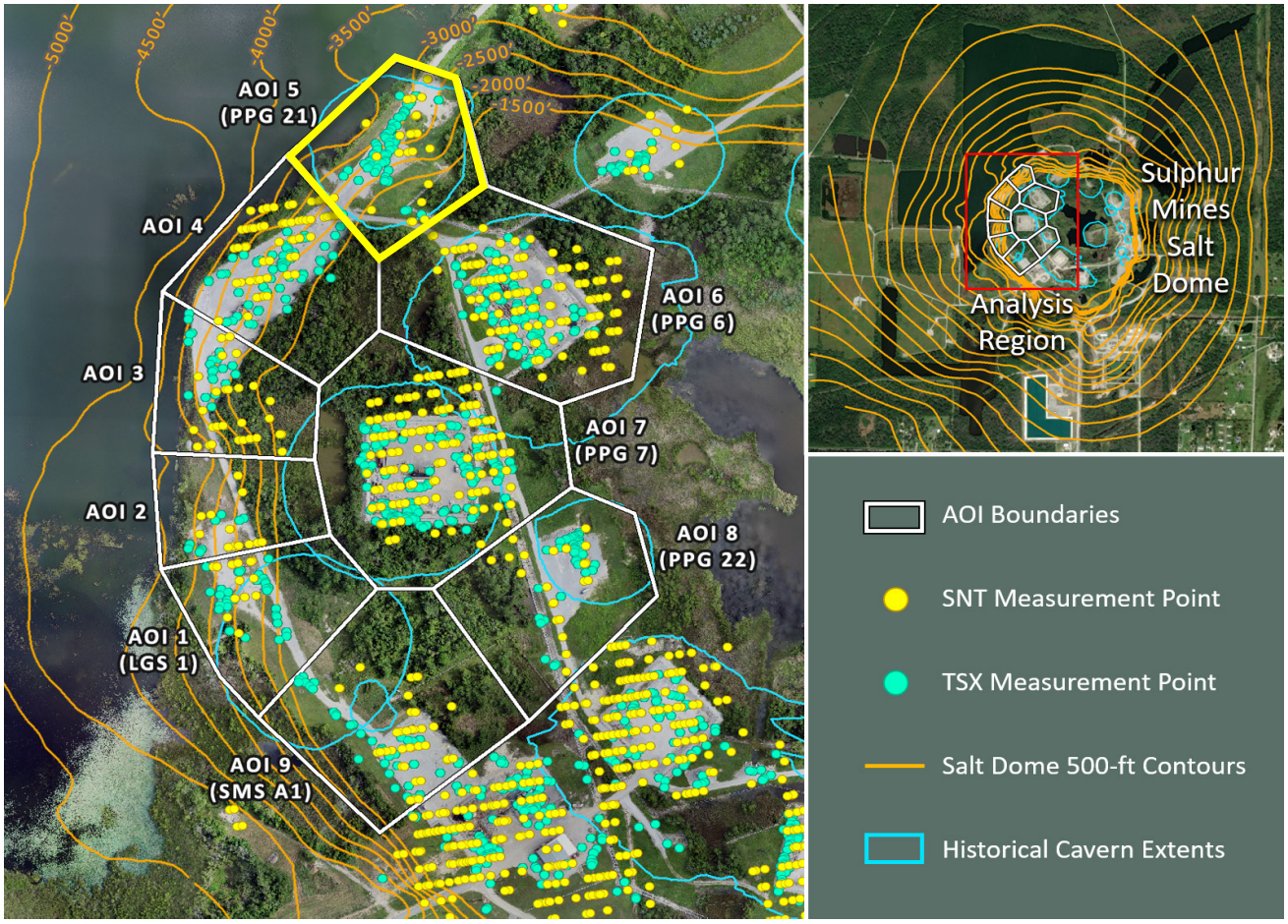
SNT (8/17/2023) Point Count: **62**




| | Historical Trend Values | Recent Trend Values | Trend Change |
|---|---|---|---|
| Velocity: | -0.73 in/yr | -0.63 in/yr | +0.10 in/yr |
| Acceleration: | +0.02 $in/yr^2$ | +0.13 $in/yr^2$ | +0.12 $in/yr^2$ |

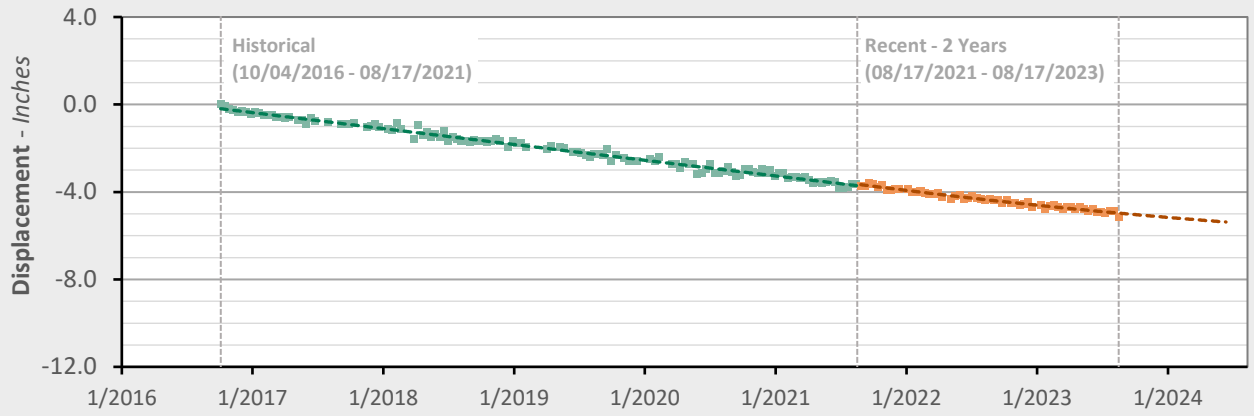
Historical LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)
Recent LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)

## AOI 5 *(PPG 21)* - Location Map




## AOI 5 *(PPG 21)* - Displacement Time Series

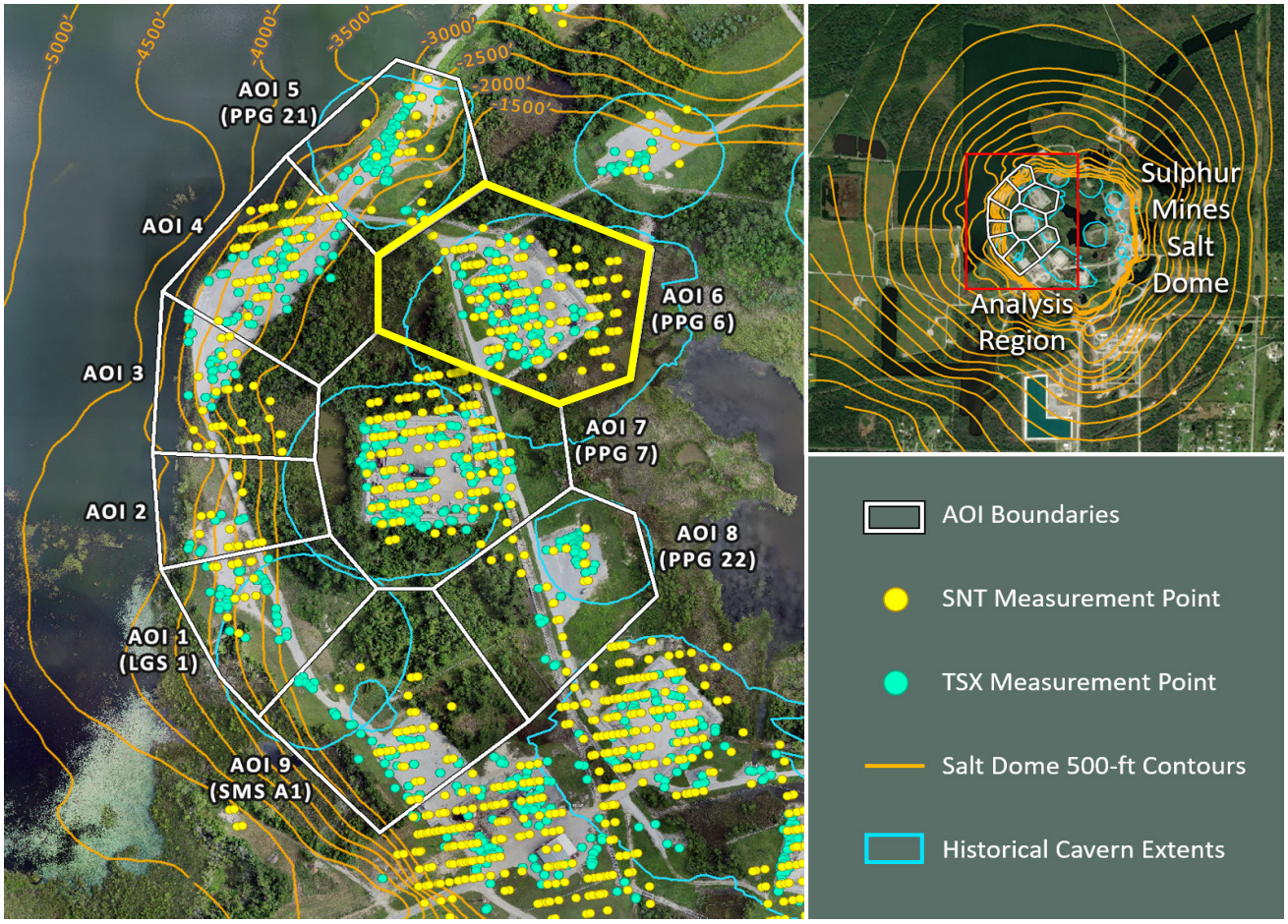
SNT (8/17/2023) Point Count: **25**




| | Historical Trend Values | Recent Trend Values | Trend Change |
|---|---|---|---|
| Velocity: | -0.71 in/yr | -0.54 in/yr | +0.17 in/yr |
| Acceleration: | +0.00 $in/yr^2$ | +0.12 $in/yr^2$ | +0.11 $in/yr^2$ |

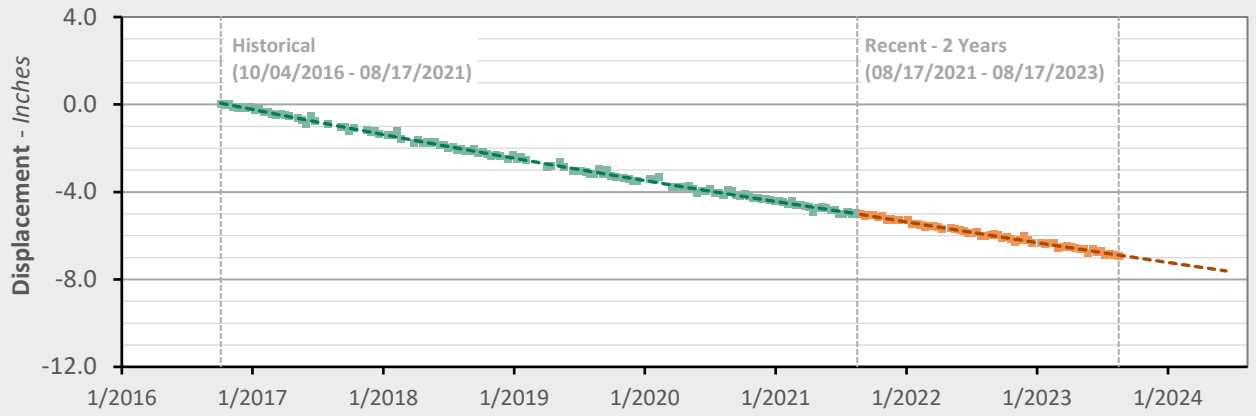
Historical LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)
Recent LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)

## AOI 6 *(PPG 6)* - Location Map




## AOI 6 *(PPG 6)* - Displacement Time Series

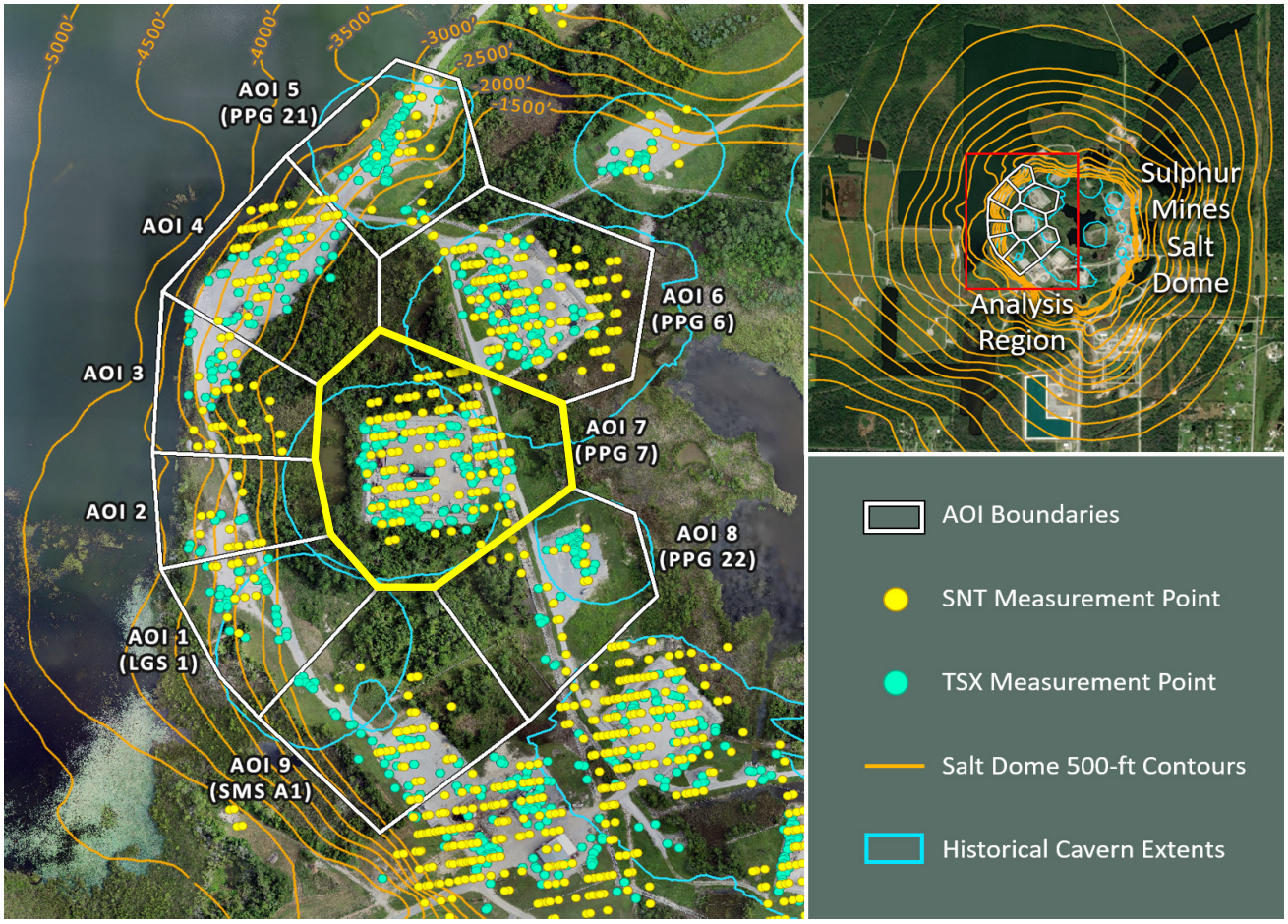
SNT (8/17/2023) Point Count: **134**




| | Historical Trend Values | Recent Trend Values | Trend Change |
|---|---|---|---|
| Velocity: | -0.88 in/yr | -0.90 in/yr | -0.01 in/yr |
| Acceleration: | +0.06 in/yr$^2$ | +0.04 in/yr$^2$ | -0.02 in/yr$^2$ |

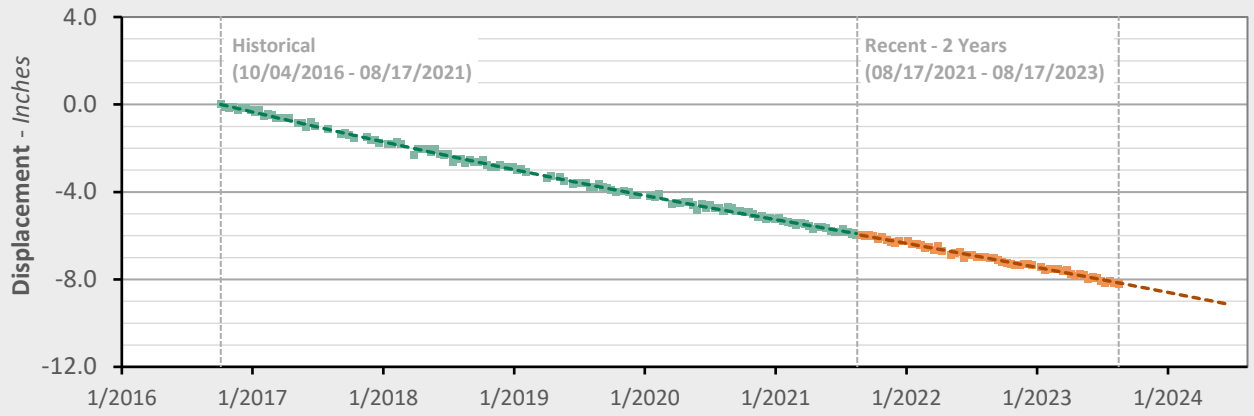
Historical LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)
Recent LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)

## AOI 7 *(PPG 7)* - Location Map




## AOI 7 *(PPG 7)* - Displacement Time Series

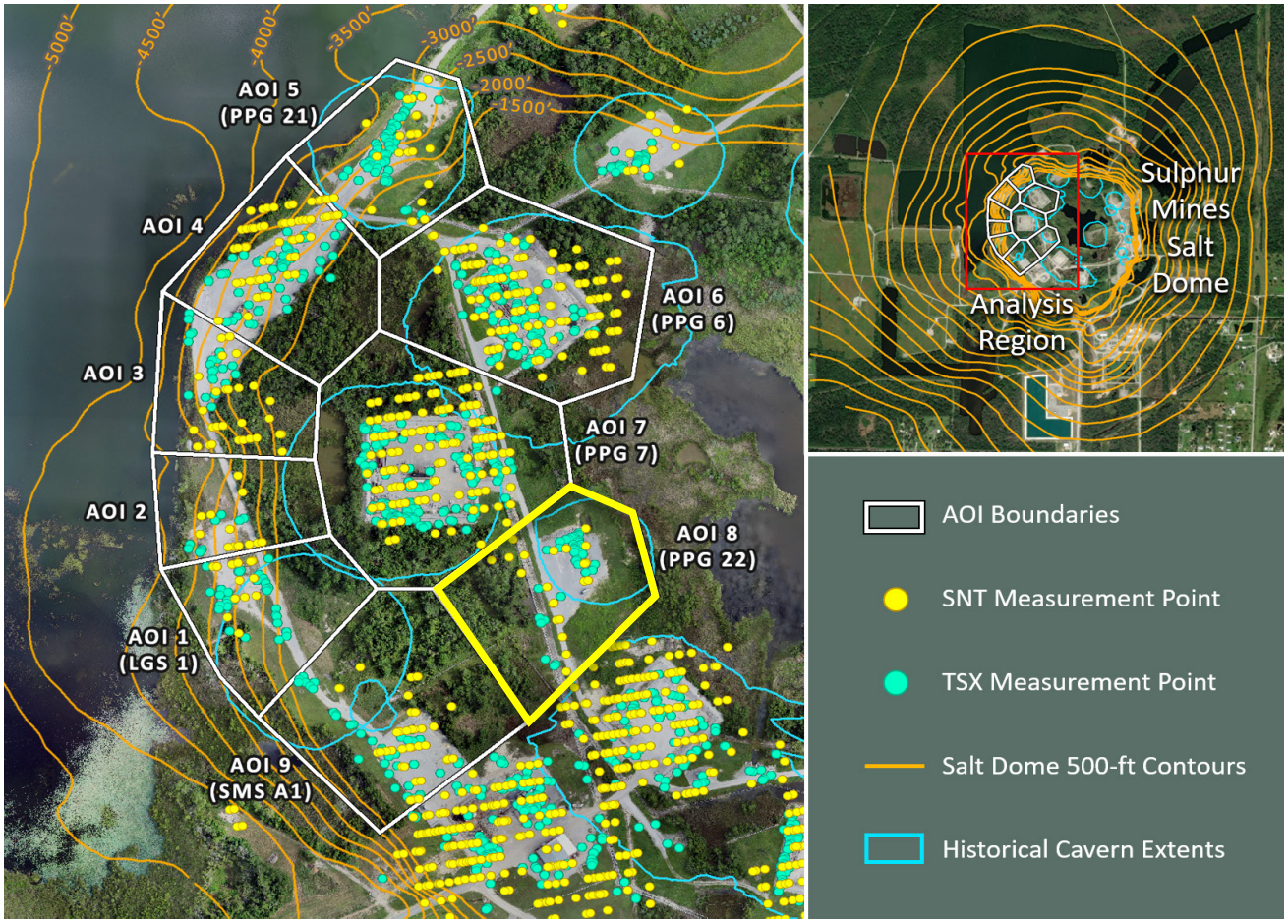
SNT (8/17/2023) Point Count: **140**




| | Historical Trend Values | Recent Trend Values | Trend Change |
|---|---|---|---|
| Velocity: | -1.00 in/yr | -1.15 in/yr | -0.15 in/yr |
| Acceleration: | +0.09 in/yr$^2$ | -0.04 in/yr$^2$ | -0.13 in/yr$^2$ |

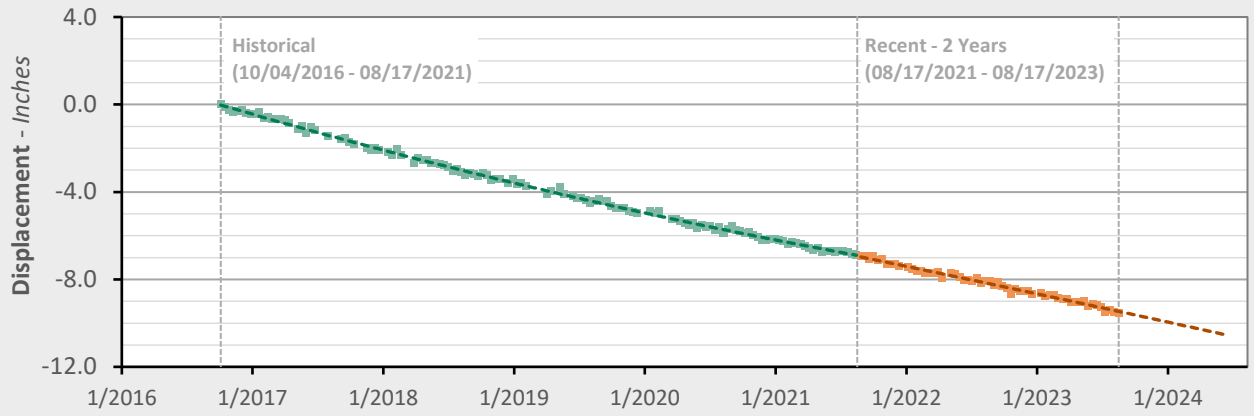
Historical LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)
Recent LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)

## AOI 8 *(PPG 22)* - Location Map




## AOI 8 *(PPG 22)* - Displacement Time Series

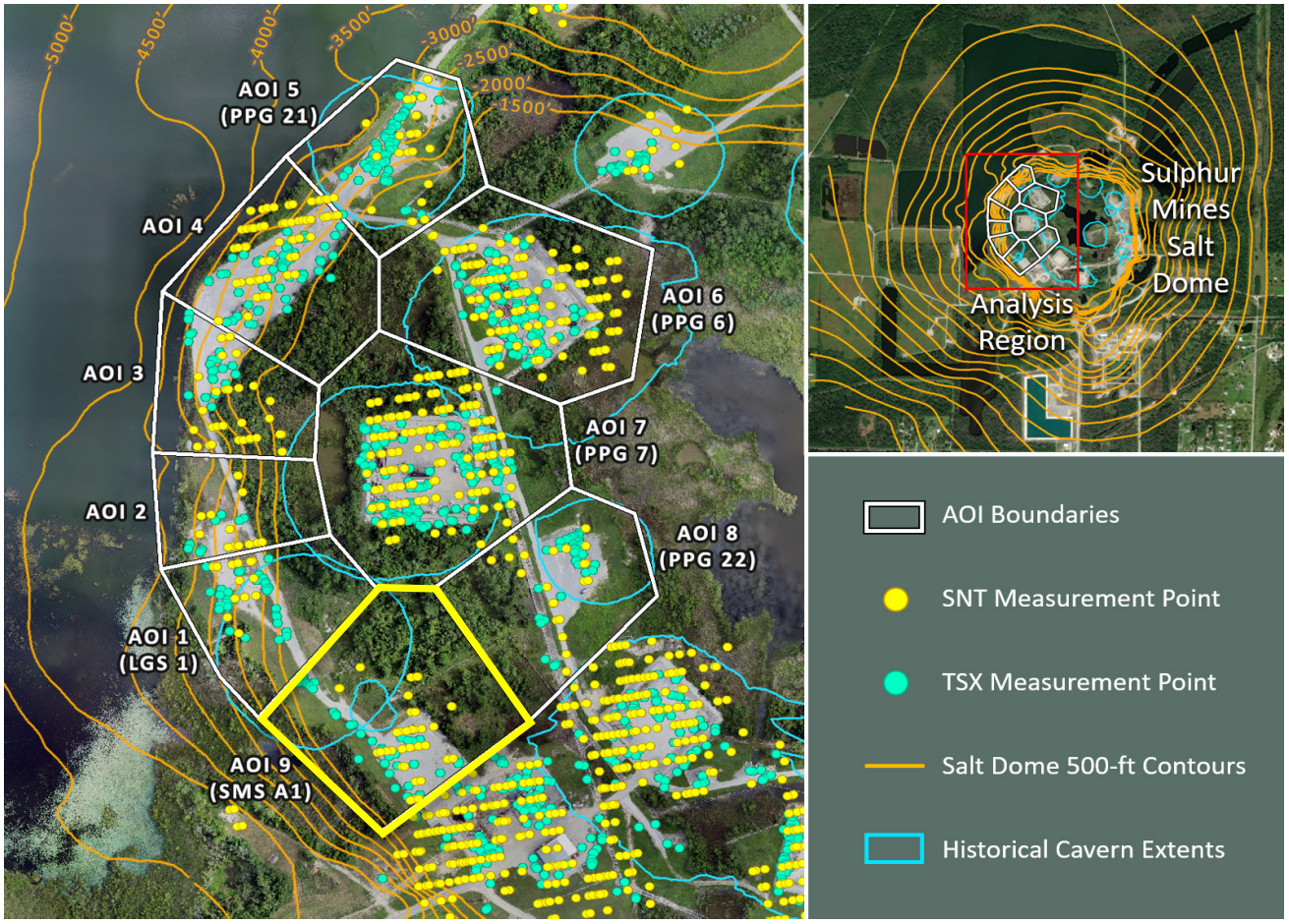
SNT (8/17/2023) Point Count: **21**




| | Historical Trend Values | Recent Trend Values | Trend Change |
|---|---|---|---|
| Velocity: | -1.08 in/yr | -1.30 in/yr | -0.21 in/yr |
| Acceleration: | +0.14 in/yr$^2$ | -0.03 in/yr$^2$ | -0.17 in/yr$^2$ |

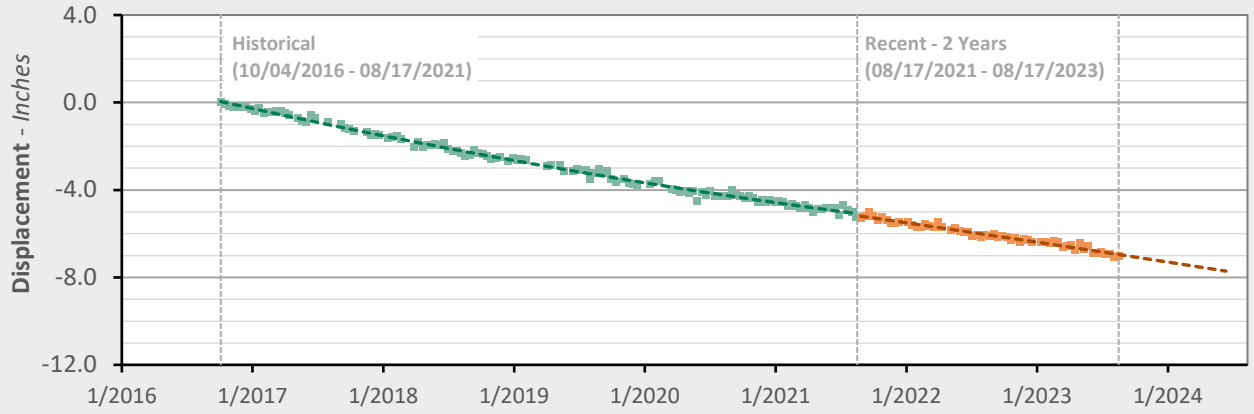
Historical LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)
Recent LOS Displacement Measurement
Historical Trend Line (Quadratic Regression)

## AOI 9 *(PPG A1)* - Location Map




## AOI 9 *(SMS A1)* - Displacement Time Series

SNT (8/17/2023) Point Count: **39**



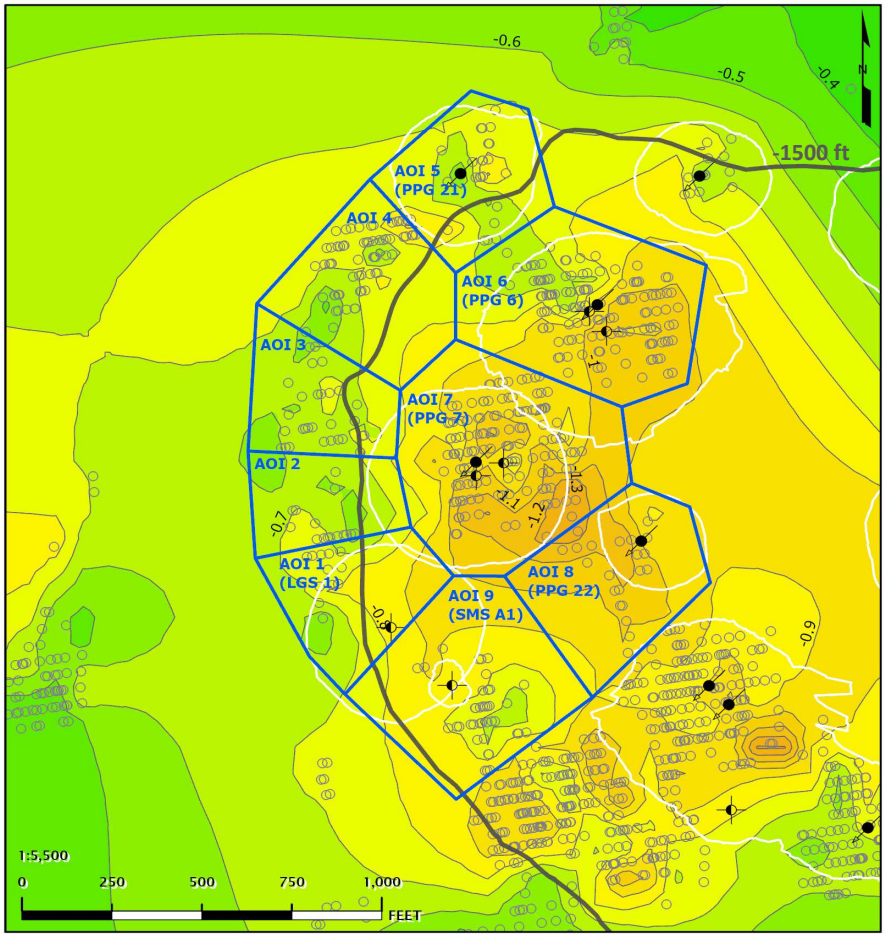

| | Historical Trend Values | Recent Trend Values | Trend Change |
|---|---|---|---|
| Velocity: | -0.78 in/yr | -0.91 in/yr | -0.14 in/yr |
| Acceleration: | +0.11 in/yr$^2$ | -0.02 in/yr$^2$ | -0.14 in/yr$^2$ |

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

## Historical SNT Data (10/04/2016 - 08/17/2021)

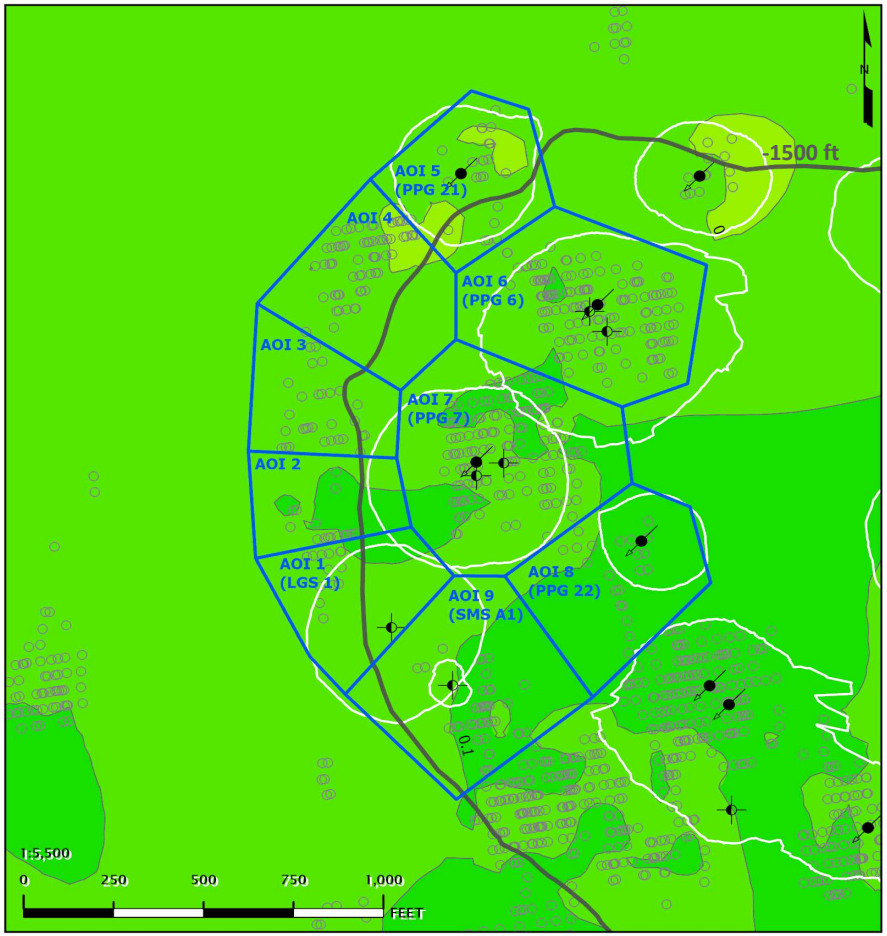
### Velocity Contours

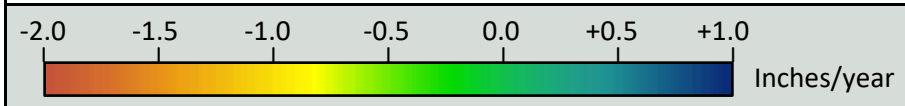
As of date: 08/17/2021




### Acceleration Contours

As of date: 10/04/2016 - 08/17/2021





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

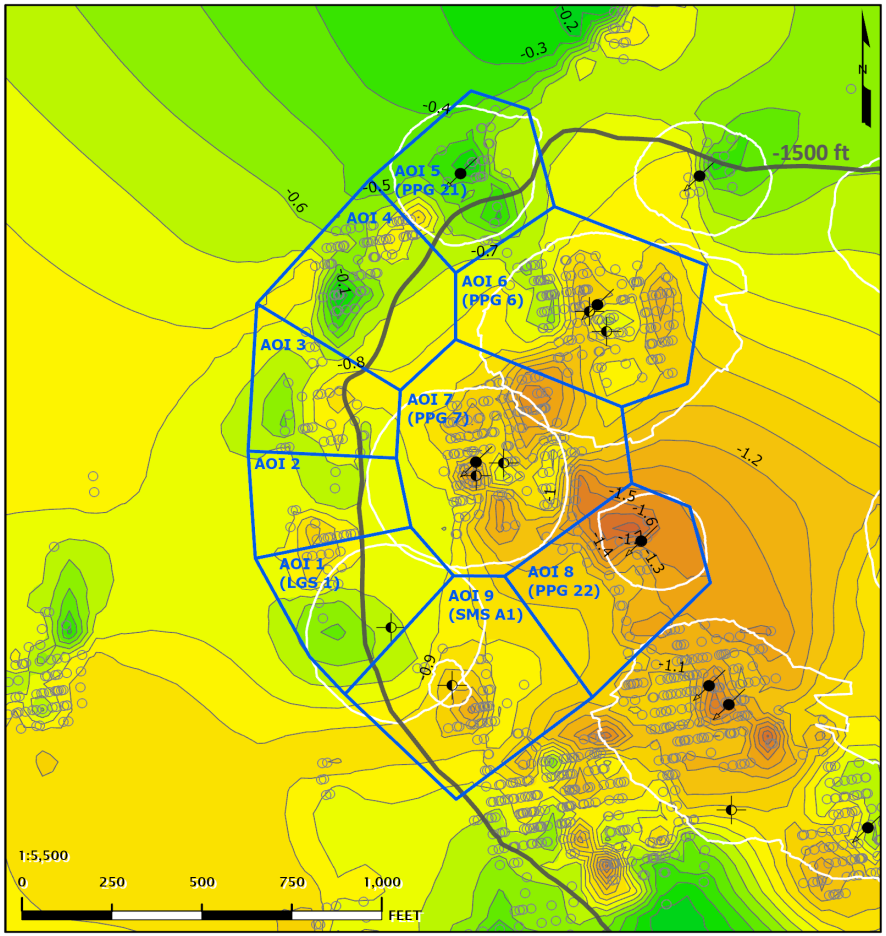
## Recent SNT Data - 2 Years (08/17/2021 - 08/17/2023)

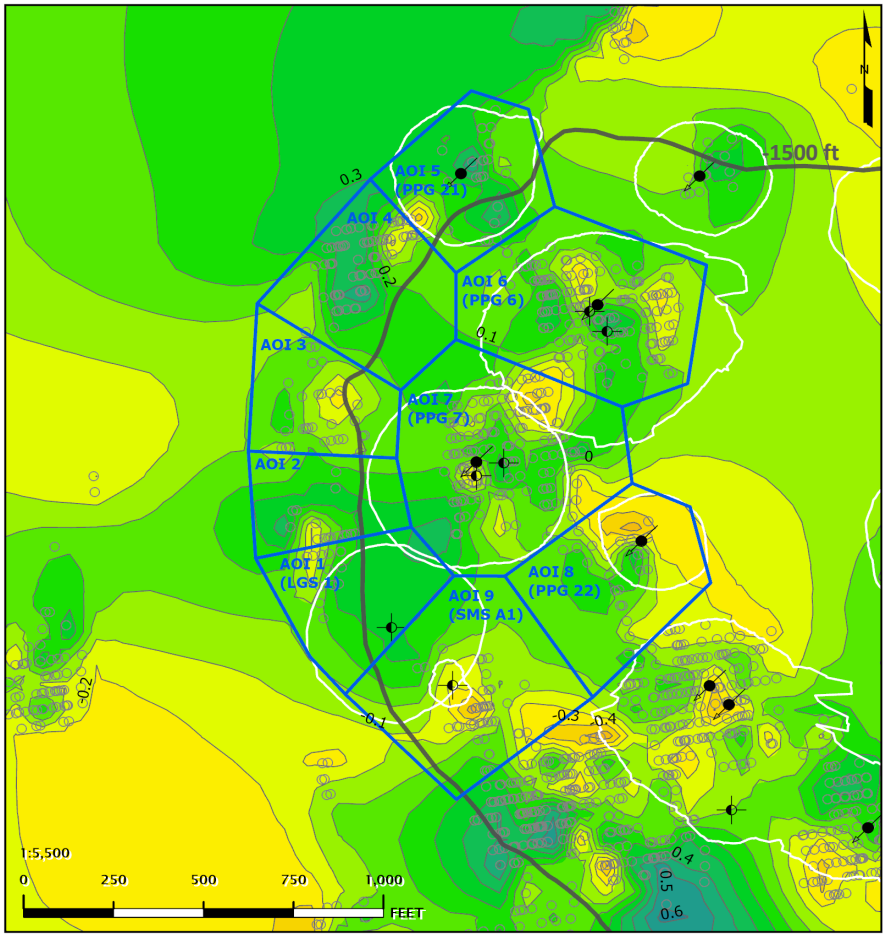
### Velocity Contours

As of date: 08/17/2023

### Acceleration Contours

Date range: 08/17/2021 - 08/17/2023




-2.0 -1.5 -1.0 -0.5 0.0 +0.5 +1.0 Inches/year

-1.0 -0.5 0.0 +0.5 +1.0 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

## Change from Historical to Recent SNT Data

### Velocity Contours

Historical Velocity subtracted from Recent Velocity

### Acceleration Contours

Historical Acceleration subtracted from Recent Acceleration