Surface Seismic Monitoring Report
Sulphur Mines Salt Dome
Semi-Permanent and Broadband Seismic Arrays

Report Period : November 1-15, 2023

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Using results from Nanometrics

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1. Sulphur Mines Dome Semi-Permanent Array

- All seven semi-permanent seismic stations were removed on November 3, 2023.
- One seismic detection was observed on November 1, 2023 at 11:48 PM local time on the semi-permanent surface seismic array. The detection was not a "measurable microseismic event" but it is discussed in detail below.

Semi-Permanent Array Status

All seven semi-permanent seismic stations were removed on November 3, 2023 by Jarpe Data Solutions (Figure 1, Table 1). The semi-permanent array is now permanently decommissioned.

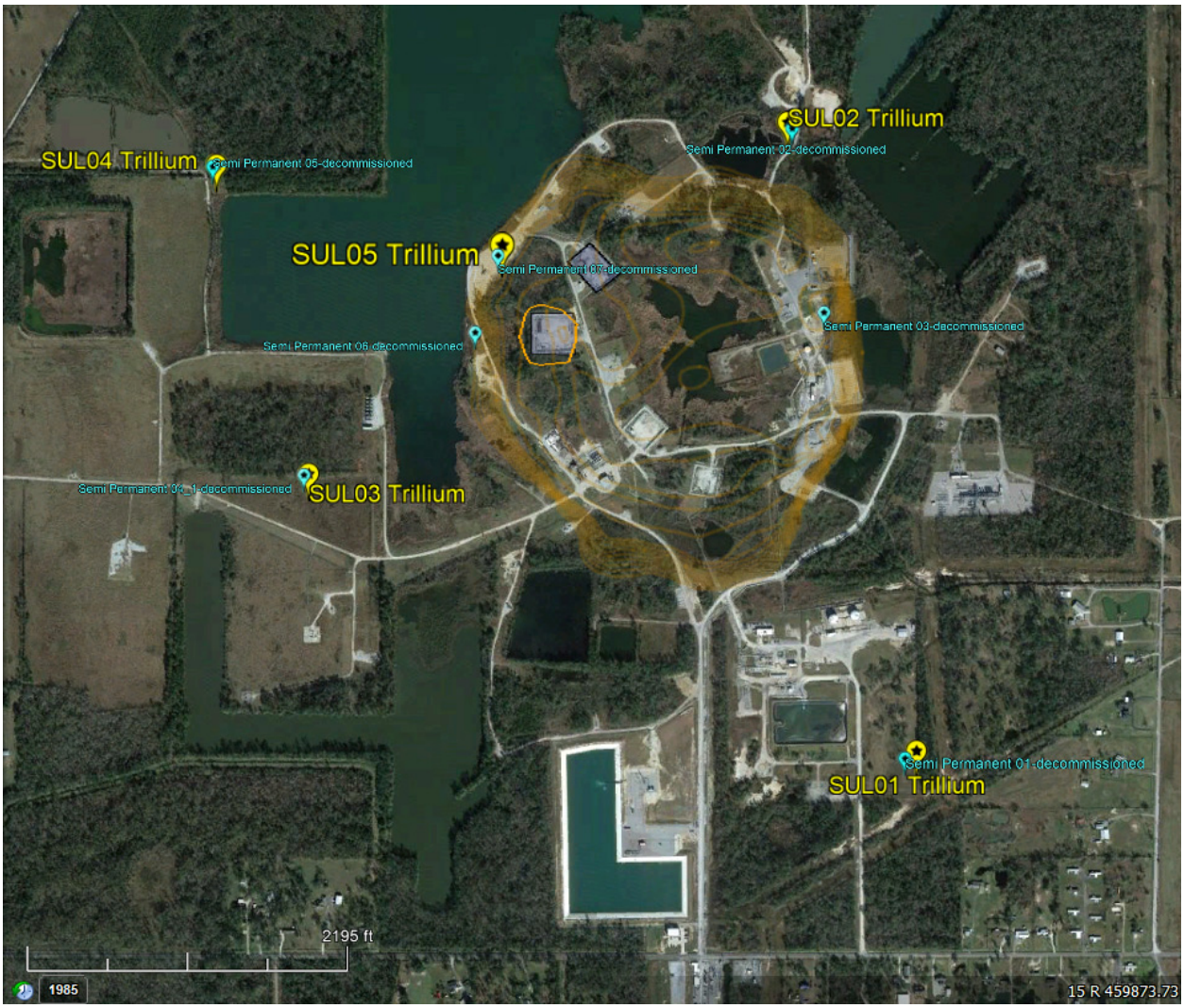


Figure 1. Google map image showing the location of the decommissioned semi-permanent (4.5 Hz sensors, aqua symbols and labels) and broadband seismic (Trillium Compact Sensors, with yellow symbols and labels) stations near and at the Sulphur Mines Salt Dome.

2. Broadband Trillium Compact Seismic Array

Nanometrics (https://nanometrics.ca/home) operates and processes data for the broadband array. The broadband array was fully functional from November 1-9, 2023. On November 9, 2023, station SUL02 malfunctioned. The station is scheduled for a maintenance visit on November 20, 2023.

The broadband station locations are show in Figure 1 and listed in Table 1. Figure 3 shows the broadband network amplitude over time from November 1 – 15, 2023 (background noise plot). The noisiest station continues to be SUL01 and the quietest station in this time period was station SUL03.

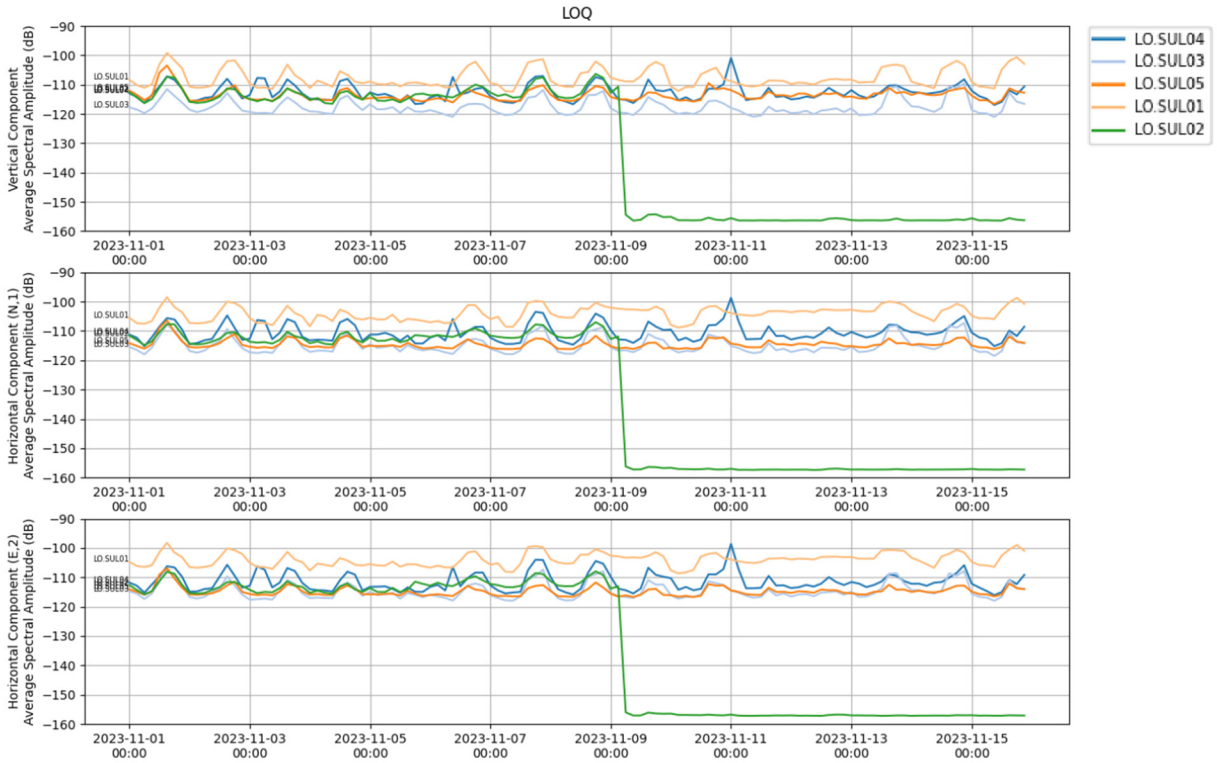


Figure 2. Average spectral amplitudes in decibels on the five broadband sensor from November 1-15, 2023. The upper plot is the vertical component, the middle and lower plots are the horizontal component (middle is north-south and lower plot is east-west component).

November 1 Detection. A seismic detection was recorded on November 1 at 11:48 PM local time. Seismic energy was recorded on both the semi-permanent array and three stations of the broadband array (Figure 3). The event was not located as the arrivals were only visible on three of the broadband stations. No location or magnitude was assigned to this event.

From the observable P-wave and S-wave arrival times we know the following about the November 1 event detection:

- Likely the energy emanated from the east side of the salt dome based on arrival times.
- The S-wave arrival time minus P-arrival time (S-P) on the stations SUL03, SUL04 and SUL05 are not compatible with an event near Cavern 7 (Figure 5).

Figure 4 shows the modeled S-wave arrival time minus P-wave arrival time for an event located at 2500 ft depth near Cavern 7. Two different velocity models are shown: 1) for an event location on the salt dome, “ONsalt” and 2) for an event location off the salt dome (“OFFsalt”) (Figure 4).

Figure 5 shows the observed S-P times for the November 1 11:48 PM seismic detection, with the modeled S-P times for an event at 2500 ft at Cavern 7 for both on-dome and off-dome velocity models. From the review of the available arrival time data and comparing the times with the modeled S-P times for an event occurring near Cavern 7, we are confident the detection observed on November 1 did not occur near Cavern 7.

The on-dome and off-dome S-P time travel time maps will serve as a general guide for assessing future seismic detections. The development of a full 3D velocity model is under way to enhance the data processing effort.

In addition, we have requested permission from Louisiana Department of Natural Resources to modify the broadband array to 1) move station SUL01 in an attempt to lower the background noise level. and 2) add an additional station to the east of the salt dome to help with azimuthal station coverage across the salt dome ("Plan to monitor microseismicity at Sulphur Mines Salt Dome: Modifications to the Broadband Seismic Array", submitted on November 15, 2023).

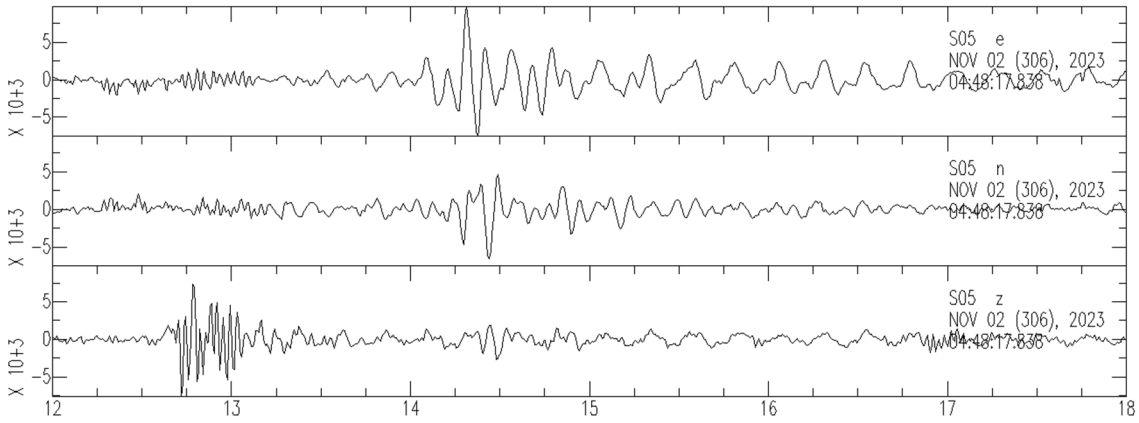


Figure 3. Waveforms recorded on the 4.5 Hz geophone at semi-permanent station 5 on November 1 11:48 (UTC time November 2 04:48). The upper plot is the east component, the middle plot the north component the lower plot is the vertical component. The scale on the bottom is seconds.

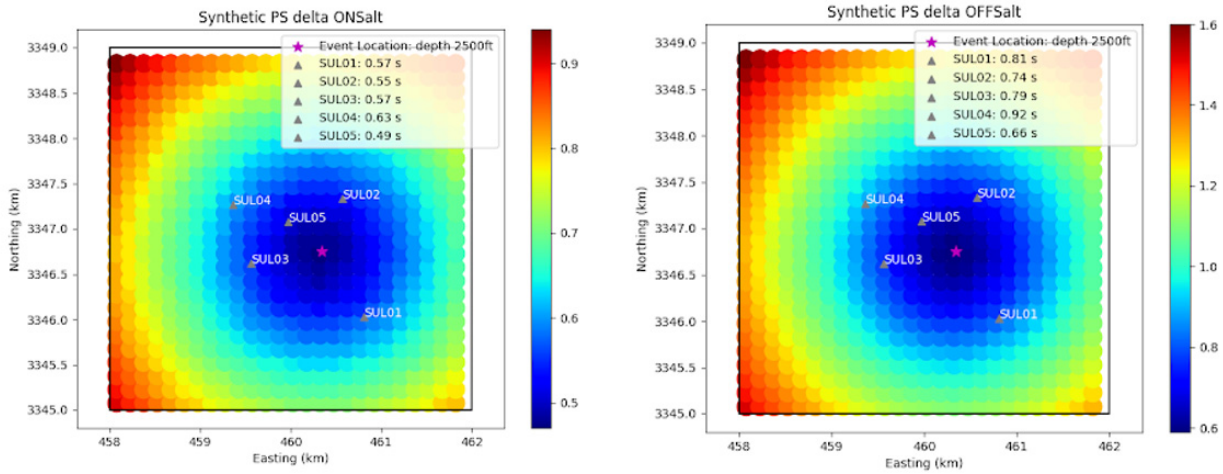


Figure 4. Modeled S-wave minus P-wave travel times for a theoretical event occurring at Cavern 7 at 2500 ft depth. The left plot shows travel times for an event within the salt dome ("on salt") and the right plot shows the travel times for events outside the salt dome ("off salt"). The S-P time for each station is listed on each plot.

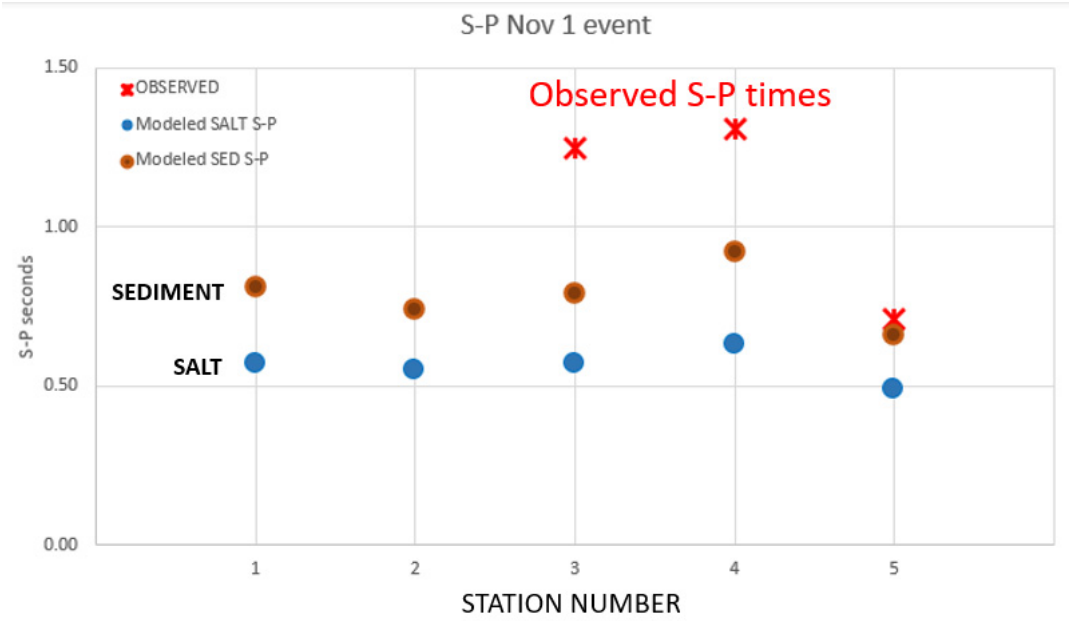


Figure 5. A graph of the observed S-P times on the broadband station for the seismic detection on November 1. The plot also shows the modeled S-P times for an event either on the salt dome (blue dots) or sediments near Cavern 7 (brown dots) at 2500 ft depth. The red stars are the observed S-P times at Station 3, 4 and 5 which are not compatible with an event near Cavern 7.

The magnitude detectability of the network for three representative noise periods is shown in Appendix 2. The modeling was updated to show the magnitude of completeness for three different attenuation values from high attenuation (Q= 100) to lower attenuation (Q=200).

Appendix 1. Station Locations

Table 1. Seismic Station locations and operational dates at Sulphur Mines Dome (to November 17, 2023). Temporary Station locations and start and end dates provided by Westlake. Trillium station locations provided by Nanometrics.

Station	LAT WGS84	LON WGS84	Date start	Date end
Temp_1a	30.2575	-93.4123	1/30/2023	2/9/2023
Temp_1b	30.2534	-93.4135	2/9/2023	4/3/2023
Temp_2a	30.2570	-93.4097	1/30/2023	2/9/2023
Temp_2b	30.2555	-93.4132	2/9/2023	2/27/2023
Temp_2c	30.2547	-93.4138	2/27/2023	4/5/2023
Temp_3a	30.2533	-93.4091	1/30/2023	2/9/2023
Temp_3b	30.2563	-93.4146	2/9/2023	4/5/2023
Temp_4a	30.2486	-93.4123	1/30/2023	2/27/2023
Temp_4b	30.2507	-93.4121	2/27/2023	3/8/2023
Temp_4c	30.2506	-93.4100	3/8/2023	3/15/2023
Temp_4d	30.2503	-93.4119	3/15/2023	est 4/3/2023
Temp_5a	30.2502	-93.4156	1/30/2023	2/27/2023
Temp_5b	30.2507	-93.4153	2/27/2023	3/15/2023
Temp_5c	30.2504	-93.4140	3/15/2023	est 4/3/2023
Temp_6a	30.2532	-93.4166	1/30/2023	3/15/2023
Temp_6b	30.2529	-93.4161	3/15/2023	4/4/2023
Temp_7a	30.2547	-93.4161	1/30/2023	4/3/2023
Semi Perm S01	30.2453	-93.4073	4/4/2023	11/2/2023
Semi Perm S02	30.2571	-93.4098	4/6/2023	11/2/2023
Semi Perm S03	30.2536	-93.4091	4/6/2023	11/2/2023
Semi Perm S04	30.2470	-93.4213	4/5/2023	5/12/2023
Semi Perm S04_1	30.2506	-93.4204	5/12/2023	11/2/2023
Semi Perm S05	30.2564	-93.4224	4/5/2023	11/2/2023
Semi Perm S06	30.2532	-93.4167	4/5/2023	11/2/2023
Semi Perm S07	30.2547	-93.4162	4/5/2023	11/2/2023
SUL01 trillium	30.2452	-93.4071	9/13/2023	
SUL02 trillium	30.2570	-93.4099	9/13/2023	
SUL03 trillium	30.2504	-93.4203	9/12/2023	
SUL04 trillium	30.2562	-93.4223	9/12/2023	
SUL05 trillium	30.2546	-93.4161	9/13/2023	

Appendix 2. Broadband Array Magnitude of Completeness (M_c)

A magnitude of completeness, Mc, is the minimum magnitude locatable on a network. For the Sulphur Mines broadband array, Nanometrics modeled three Mc scenarios for the array based on three noise levels, high, median and low noise recorded from September 20 to 27, 2023 (Figure 6). The magnitude of completeness model assumes 4 stations are triggered to compute a location. The Mc events are modeled at 3000 ft depth, near the base of Cavern 7, using three different noise levels based on the noise recorded on the array. The percentile used are 10^{th} (low noise), 50^{th} (median noise) and 90^{th} (high noise) (Figure 6).

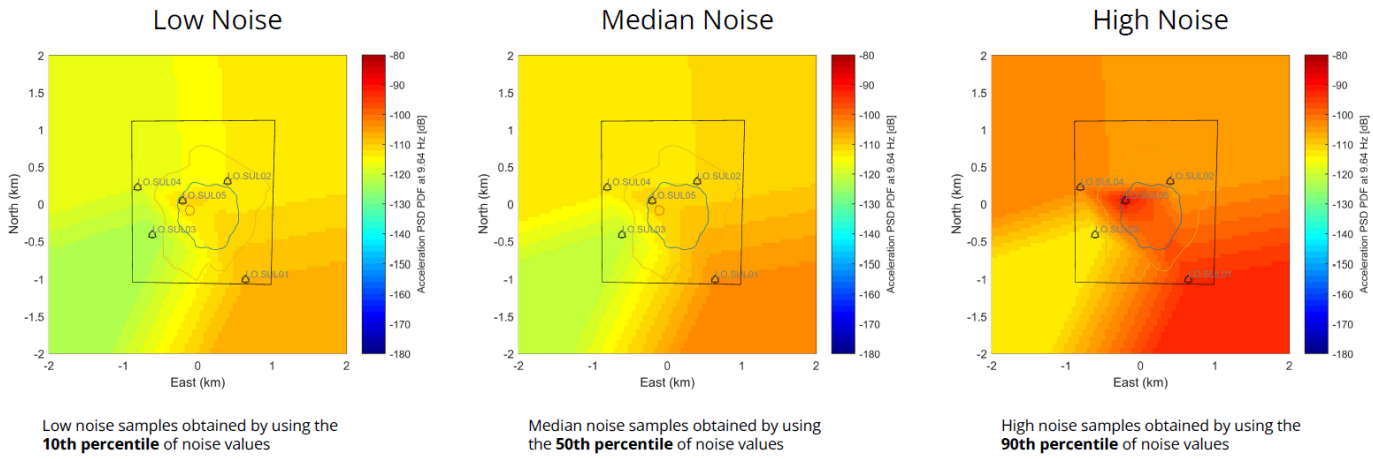


Figure 6. Map of the noise levels modeled for the magnitude of completeness figures. Left most is the low noise, middle median noise and right is high noise.

The map of the magnitude of completeness modeled by Nanometrics for the three noise levels is shown in Figure 7 for the Sulphur Mines dome area. The Mc will vary spatially (Figure 7) depending on the station geometry and the event location and depth.

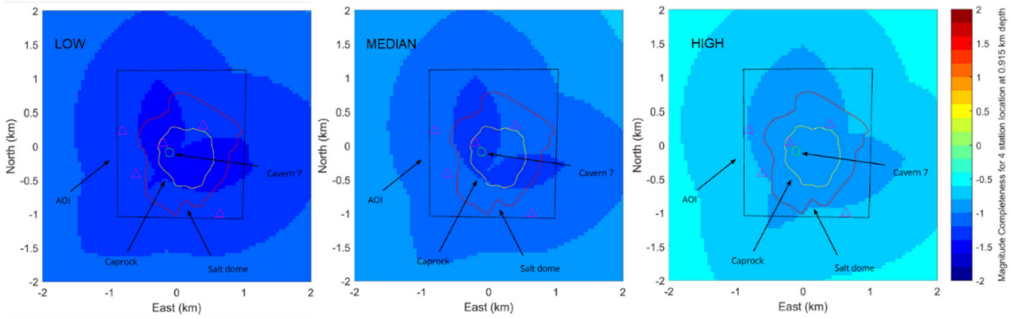
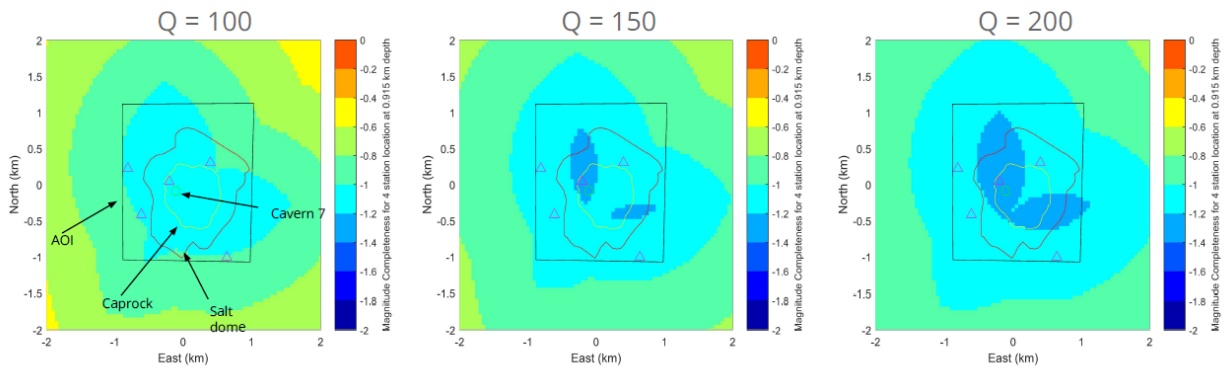


Figure 7. Modeled magnitude of completeness (Mc, lowest magnitude detectable) for the Sulphur Mines salt dome and vicinity using the broadband array. Three noise models are shown: the high noise model shown on the right, median noise level in the middle and low noise model on the left, as labeled. The outline of the Sulphur Mines dome and caprock and the outline of Cavern 7. The color bar shows the Mc values for each model.

Modeling with Seismic Attenuation. Seismic attenuation will result in a modification of the magnitude detectability across the array. If seismic attenuation is high, more energy is dissipated therefore is more difficult to record seismic waveforms on the surface. Figure 8 shows magnitude of completeness for the median noise level for three seismic attenuation values.



- **Range:** M-1.18 to M-0.81
- **Median:** M-1.05
- **Cavern 7:** M-1.15

- **Range:** M-1.24 to M-0.93
- **Median:** M-1.13
- **Cavern 7:** M-1.21

- **Range:** M-1.27 to M-0.99
- **Median:** M-1.17
- **Cavern 7:** M-1.25

Figure 8. Modeled magnitude of completeness (Mc, lowest magnitude detectable) for the Sulphur Mines salt dome and vicinity using the broadband array for three different seismic attenuation values for a median noise level. The three seismic attenuation values are on the top of each plot: Q=100 (high attenuation), left most plot, Q=150 (medium attenuation, middle plot) and Q=100,(lower attenuation, right plot). The outline of the Sulphur Mines dome and caprock and the outline of Cavern 7. The color bar shows the Mc values for each model.

The modeling results for Mc computed by Nanometrics at Cavern 7 location at 3000 ft depth suggests:

- The low noise model shows a Mc of about magnitude -1.4
- The median noise level Mc is magnitude -1.3.
- For the median noise level and accounting for seismic attenuation:
    - With Q= 100 seismic attenuations (highest attenuation modeled), the estimate is M -1.15
    - With Q=150 seismic attenuation, the estimate is M -1.13
    - With Q=200 seismic attenuation (lowest attenuation modeled), the estimate is M -1.25
- The high noise level Mc is magnitude -0.9.