

Technical Memorandum

TO: Louisiana, Department of Natural Resources, Injection Mining Division

FROM: Julie Shemeta, MEQ Geo Inc. for Westlake/Lonquist

Date: June 5, 2024



RE: Borehole microseismic system installation Sulphur Mines Dome and proposed initial Seismic Alert System

This memo summarizes the current state of the two borehole microseismic arrays installed at Sulphur Mines in mid- April 2024 and proposes an initial Microseismic Alert Level for an Area of Interest in proximity to Cavern 7.

Borehole Geophone Sensor installation. Two borehole arrays are installed at Sulphur Mines Dome in wellbores PPG No. 006-X and PPG No. 020 (Figure 1). The array installations were performed from April 17-20, 2024. As of June 4, 2024, all geophone sensors are operational in both wellbores.

The seismic arrays in each well were built by Avalon™ and consist of 3-component (3C) Geospace™ Omni 15 Hz sensors: a vertical and two orthogonal horizontal geophones. A time-delayed locking arm at each sensor clamp the geophones to the cavern wellbores. The geophones are located in the wellbore above the cavern. The geophones in PPG No. 020 are placed at 1820, 2055, 2315, 2750, 2950, and 3200 ft depth and PPG No 006-X at 1860, 1985 2110, 2235, 2360, and 2485 ft depth (Figure 1). The Avalon™ arrays are designed to allow the removal and re-installation of the arrays if access to the wellbore and cavern is required.

The geophones clamped to the wellbores sense ground motion and are continuously digitized at 2000 Hz at the surface with digitizing equipment located near each well head. The surface equipment performs preliminary data processing on the ground motion data and “triggers” the seismic system to extract potential seismic events from the continuous data stream. The triggered packet of ground-motion data is transmitted in real-time for further review and processing, described in more detail below. The surface equipment is placed on special metal platforms to keep the electrical equipment above potential flooding in the area.

Sensor orientation and initiation of microseismic monitoring. Microseismic event locations are computed using the arrival times of seismic energy from the microseismic event and the direction the energy is traveling from (the event azimuth). To calculate event azimuth, the geographical orientation of each horizontal sensor must be determined. To orient the borehole geophones, a series of seismic pulses were deployed using a 500 lb. Accelerated Weight Drop (AWD). The orientation source positions were taken around the Sulphur Mines dome on April 25, 2024. Subsequent analysis of the AWD seismic data revealed additional calibration was needed and two string shots (30 feet of 80 grain prima cord) were deployed and detonated in PPG No. 002 wellbore on May 24, 2024. The horizontal component sensor calibration was completed and microseismic data processing for location X-Y-Z and magnitude estimates started in late May 2024. The data processing commenced with data starting on April 21, 2024, the day the borehole array installations were completed. The seismic arrays performance will be monitored over the first few weeks to determine the ambient background noise level and magnitude sensitivity of the borehole arrays.

Microseismic Data Processing The microseismic data processing for the Sulphur Mines microseismic arrays is currently contracted to Baker Hughes, using the Microseismic Services division located in Ste. Tulle, France. Paraphrasing information provided by Baker Hughes: the ongoing microseismic data processing is partly automatic and manual. Automatic microseismic data processes run 24 hours per day/7 days per week and identify “candidates”, i.e., possible microseismic events. Each working business day in France a technical expert reviews all the candidate microseismic events and confirms if the candidate trigger is a microseismic event or a noise or other type of non-seismic trigger. For verified events, the analyst will then determine the microseismic time and the X-Y-Z position, and estimate the event size, or magnitude.

In addition, to triggering the microseismic acquisition system, automatic processing is also checking the “state of health” of the ground motion data quality and any issues with the incoming data stream. Another automatic process is constantly reviewing the data stream for any potential large magnitude events. If a large microseismic event is detected, an automatic system sends a notification to the data processing team 24/7 if a Peak Ground Velocity (PGV) or Magnitude threshold is exceeded. The potential “large” event is reviewed and processed within 24 hours on Monday – Friday, business working days in France. The magnitude threshold and time period for review are defined within the Microseismic Alert System, described in more detail below.

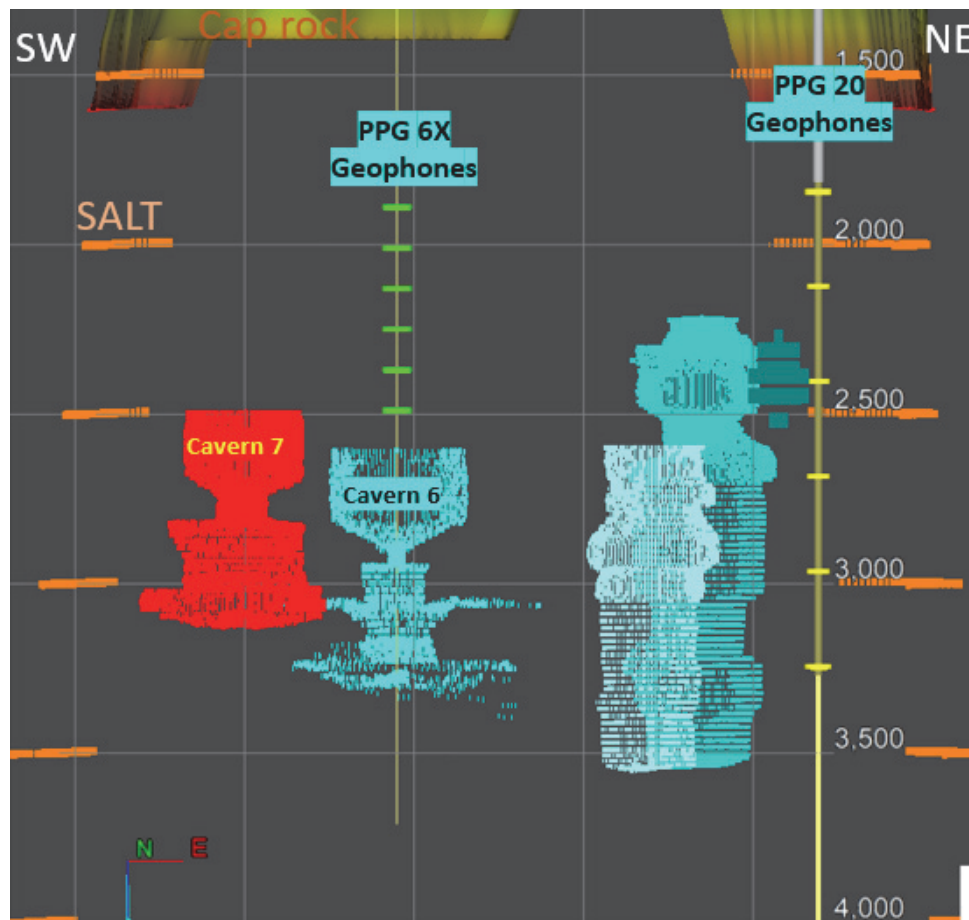


Figure 1. Cross section view of geophone positions in PPG 6x and PPG 20 (hash marks along the wellbore) at Sulphur Mines Dome. Sonars for several caverns are shown. The salt and cap rock positions are labeled.

Microseismic Alert System. We propose an initial Microseismic Alert System for Sulphur Mines Dome. Microseismic data has been collected at Sulphur Mines dome since late January 2022 at Sulphur Mines using a variety of surface sensors and array geometries. The current surface seismic array is a Nanometrics surface broadband seismic array which has located several events near the dome flanks, but none that appear directly related to the Sulphur Mines salt dome caverns or proximal to Cavern 7. The magnitude detection threshold of the current surface array is estimated at about magnitude -0.75 (Shemeta, 2024a). Over time, the borehole microseismic events will provide more accurate detection thresholds for the surface seismic array.

The April 21 to May 31, 2024 borehole microseismic report revealed 16 microseismic events and 41 seismic detections located on the Sulphur Mines dome, ranging in magnitude from -1.9 to 0.9 (Shemeta, 2024b). No microseismic events were located in proximity to Cavern 7 as of May 31, 2024.

Due to the paucity microseismic data directly related to the caverns at Sulphur Mines dome, we propose using microseismic data obtained at the Napoleonville salt dome related to the Bayou Corne sinkhole, related to the failure of 2012 Oxy Geismar 3 cavern for creating thresholds for the initial Microseismic Alert System at Sulphur Mines dome. The Napoleonville Dome is located about 138 miles east of Sulphur Mines dome. As more data is collected at Sulphur Mines Dome, the alert system can be revised if necessary.

The Napoleonville microseismic data volumes were obtained from both a surface seismic array operational in mid-July 2012 prior to the formation of the initial sinkhole in early August 2012 and a microseismic observation well located near the failed cavern with a borehole microseismic array which was operation in October 2013 and is still in operation today.

Nayak (2017) documented seismicity recorded on the surface array several weeks before the appearance of the initial slurry hole that appeared on the surface on August 3, 2012 that eventually grew to form the Bayou Corne sinkhole. A dedicated observation well G-01 (Serial Number 245928) with multiple borehole seismic arrays was operational about 14 months following the initial appearance of the sinkhole. This seismic array has been monitoring the salt and caverns near the Bayou Corne sinkhole since October 2013 and is still operational (Shemeta, 2023). We use these rich microseismic data sets collected at Napoleonville salt dome for the initial alert system at Sulphur Mines.

Four Microseismic Alert Levels are proposed for Sulphur Mines Microseismic Alert system, defined using the event magnitudes and number of seismic events reported at Napoleonville, using both pre-sinkhole microseismic activity and post-sinkhole microseismicity.

Napoleonville Pre-sinkhole Microseismic Activity. Prior to the appearance of the initial slurry hole observed on August 3, 2012 at Napoleonville salt dome, the local population reported feeling seismic events. The felt seismic reports documented by the Louisiana Office of Emergency Preparedness included a few felt events in early June 2012. Installation of a surface seismic array began about July 15, 2012 in the area to investigate the source of the felt seismicity (Ellsworth et al., 2012). Nayak (2017) used this surface seismic array data to locate the microseismicity activity prior to the formation of the sinkhole.

The magnitudes computed by Nayak are shown in Figure 2 which plots the event magnitude versus time observed in the weeks prior to the formation of the initial sinkhole. This pre-sinkhole microseismic

activity is considered “anomalous” when defining the Microseismic Alert System. We use the distribution of microseismic magnitudes reported prior to the formation of the Bayou Corne sinkhole at the Napoleonville salt dome to guide the magnitude level, and to define the upper limit for a daily microseismic event count for the Sulphur Mines Microseismic Alert system.

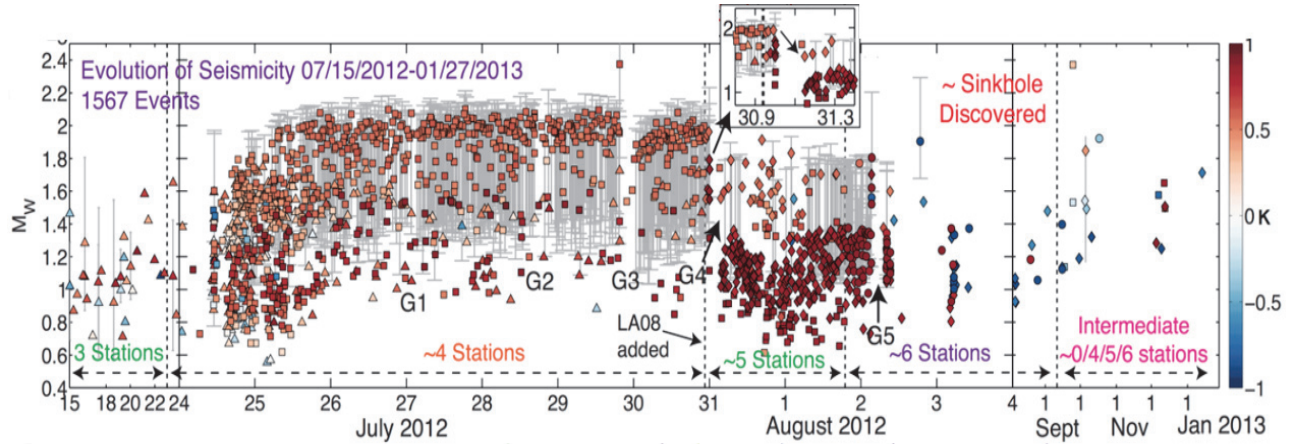


Figure 2. Pre-sinkhole magnitude vs time graph published by Nayak 2017.

Magnitude limit for Microseismic Alert System. Figure 3 shows the magnitude distributions of pre-sinkhole and a selection post-sinkhole microseismicity observed on the borehole array recorded at Napoleonville salt dome. The median seismic magnitude recorded on the surface array prior to the formation of the sinkhole is about 1.4 (Figure 3). The median magnitude recorded on the Napoleonville borehole array is magnitude -1.1, almost two orders of magnitude smaller event than observed prior to the formation of the Bayou Corne sinkhole.

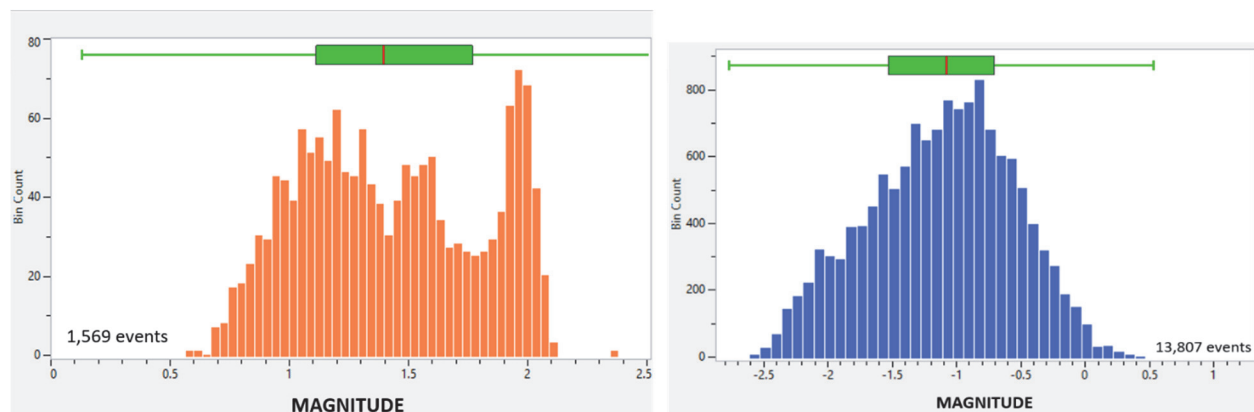


Figure 3. Histograms showing the distribution of microseismic events at Napoleonville salt dome used to define Microseismic Alert Levels for Sulphur Mines salt dome. The left figure is distribution of “anomalous” magnitudes for event reported by Nayak (2017) (see Figure 2) prior to the formation of the Bayou Corne sinkhole in 2012. The right figure is an example of the “normal” magnitude distribution for over 13,000 events recorded near the Napoleonville borehole microseismic array. Note the different magnitude scales for the histograms.

Defining the proposed Sulphur Mines Microseismic Alert System. The description of the proposed four-level microseismic Alert System for Sulphur Mines is described below including proposals for the definition of:

- Area of Interest
- Microseismic Alert Magnitude Levels
- Microseismic Activity (events per day) Alert Levels.

AOI. An Area of Interest (AOI) for microseismic event locations is proposed for Sulphur Mines dome which encompasses Cavern 7 and the salt flank to the west, as well as other adjacent caverns (Figure 4). The Microseismic Alert System initially will include all microseismic event depths, from surface to deepest event locatable within the AOI. The corner coordinates for the proposed AOI are listed in Appendix 1.

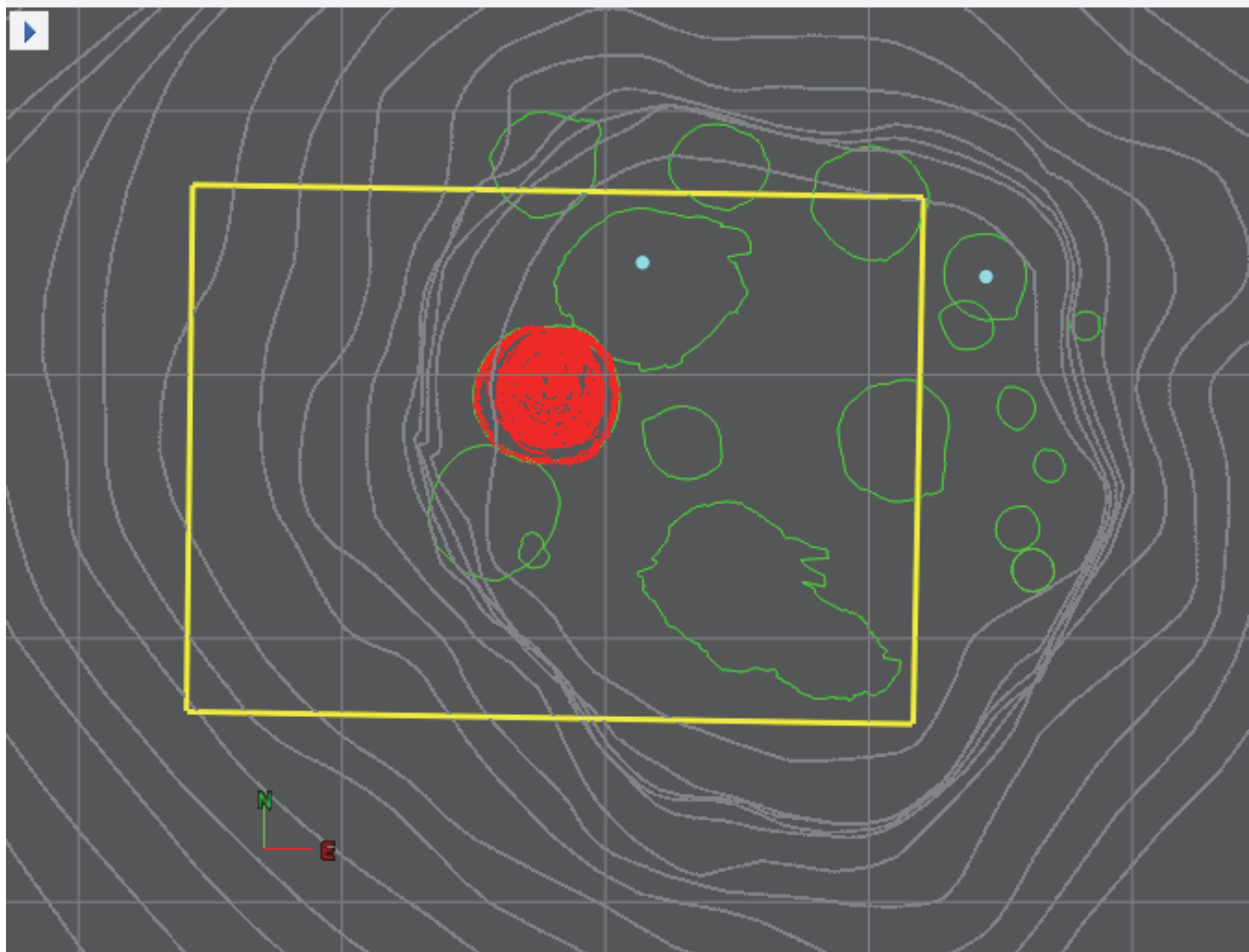


Figure 4. A map of the proposed Area of Interest (AOI) for the microseismic alert system at Sulphur Mine dome (yellow box). Cavern 7 sonar is shown in red. Other cavern outlines in green. Gray lines are the salt contours. Grid is 1000 feet. Cyan dots indicate the wellbores with geophones, PPG No. 006-X and PPG No. 20.

Alert Magnitude Thresholds. We propose for Sulphur Mines salt dome that seismic events with magnitudes greater than or equal to magnitude 0.5 as the start of possible anomalous microseismicity, based on the magnitude distributions observed at Napoleonville prior to the formation of the Bayou

Corne sinkhole (Figure 3). This magnitude is the lower limit observed by Nayak from the surface array and near the upper limit of what is considered “normal” microseismic activity for a salt dome (Figure 3).

Alert Microseismic Daily Count Threshold. To define an anomalous count of daily microseismic within the AOI for the highest alert level “Warning” or red level, we propose using 50 events per day in the AOI greater than magnitude -1, based on the pre-sinkhole distribution reported by Nayak (Figure 4). This is a conservative count considering the surface array used by Nayak for magnitude detectability was likely greater than magnitude 0 and the Sulphur Mines borehole arrays are currently recording events less than magnitude -1. Hence, we are proposing counting daily events using events an order of magnitude smaller than observed prior to the emergence of the Napoleonville Bayou Corne sinkhole.

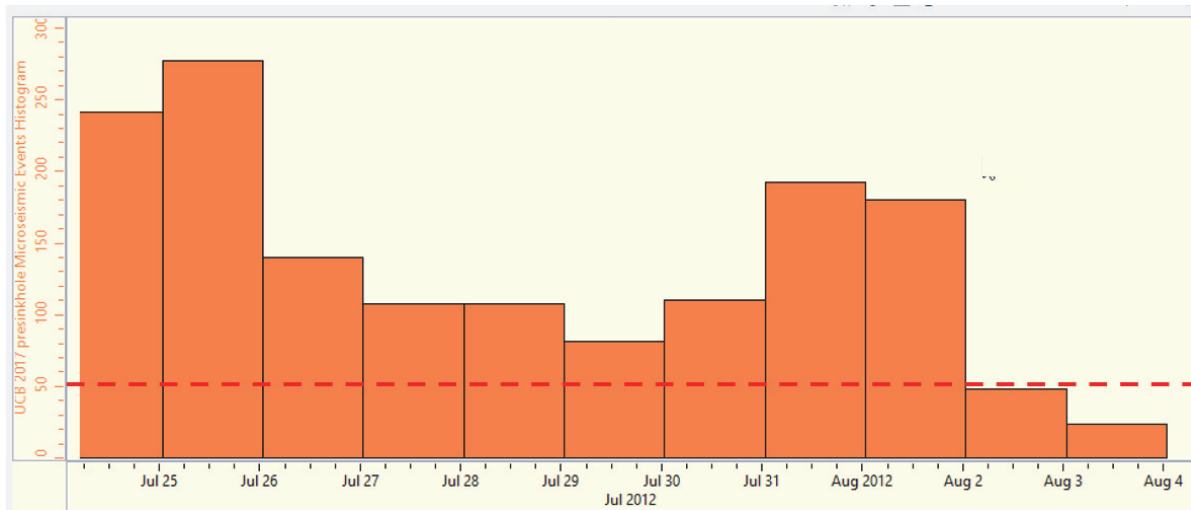


Figure 5. The number of Microseismic events per day reported by Nayak (2017) for pre-sinkhole microseismicity at Bayour Corne. The red dotted line indicates 50 events per day.

Microseismic activity is normal for an active brining and storage caverns in a salt dome (Shemeta, 2023). We seek to define a daily event count for smaller microseismic events observed to define alert levels of yellow and orange. Figure 6 shows the distribution of the event counts per day magnitude ≥ -1 observed at the Napoleonville borehole seismic array over the past 9.5 years plotted with the cumulative number of days the count was observed. We chose a magnitude -1 or larger for the daily counts at this magnitude is expected to be observed from either borehole array at Sulphur Mines within the AOI. The proposed magnitude -1 or larger event count per day for green, yellow, orange and red alert levels are indicated in the AOI in Figure 6.

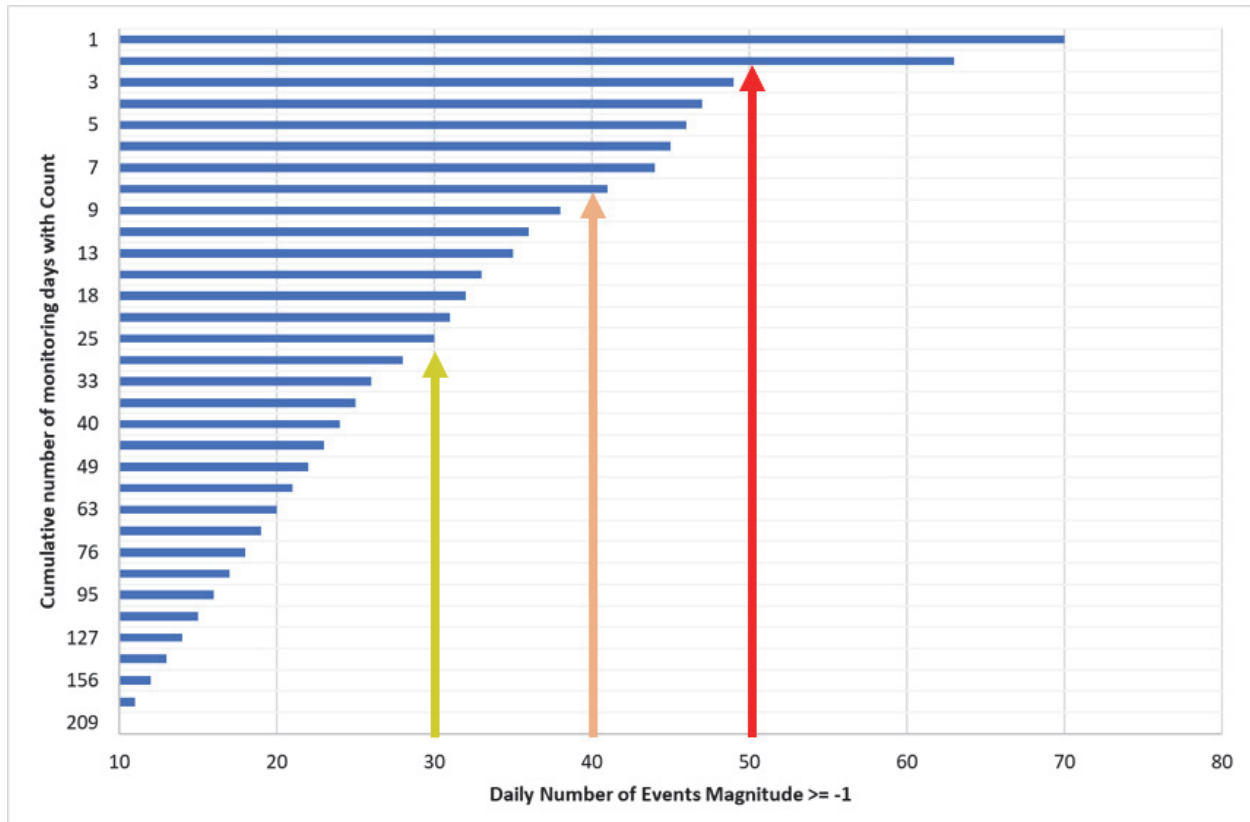


Figure 6. Graph showing the count of events magnitude ≥ -1 observed in the Bayou Corne sinkhole AOI (x-axis) and the cumulative number of days the count was observed over the past 9.5 years (y-axis). The colored arrows indicate the proposed yellow, orange and red daily number of events for each microseismic alert level for Sulphur Mines. Yellow alert level is more than 30 events per day and was observed 25 times in 9.5 years of monitoring at Napoleonville. Orange alert level is more than 40 events per day and was observed 8 times in 9.5 years at Napoleonville. Red alert level is defined as more than 50 events per day, chosen from the surface seismic array activity reported by Nayak (Figure 5). This level of activity was only observed twice at Napoleonville during the 9.5 years of monitoring.

Proposed Microseismic Alert System for Sulphur Mines Dome

A four-level Microseismic Alert System with defined levels: low (green), advisory (yellow), watch (orange) and warning (red), is proposed for Sulphur Mines salt dome and is summarized below and in Table 1. The microseismic activity reported on the borehole microseismic arrays in PPG No. 006-X and PPG No. 020 shall be used to measure the microseismic activity. The Microseismic Alert Levels described below are updated within 24 hours of a change in the microseismicity trends observed on Monday-Friday, working business days in France. Table 3 in the Appendix list National Holidays in France for 2024. The alert levels “day” is defined as midnight to midnight Central Time Zone with adjustments made to daylight savings time.

- **Low Level (GREEN)** alert level is considered “normal” levels of microseismicity at the Sulphur Mines salt dome AOI.
 - Normal is defined as no microseismic events greater than or equal to magnitude 0.5 in the AOI and/or;
 - Daily event count within the AOI greater than magnitude -1 is less than 30 events per day.

- During “normal” levels of microseismicity in the AOI, event locations and magnitude are reported once a week by processing vendor.
- LDNR IMD will receive a monthly microseismic report provided by the 15th of the following month with a summary of microseismic activity in the AOI for the previous month.
- **Advisory Level (YELLOW)** alert level is considered an elevated level of microseismicity at the Sulphur Mines salt dome.
 - Advisory (YELLOW level) is defined when microseismic events equal to or less than magnitude 0.5 but less than magnitude 1 occur within the AOI and/or;
 - Daily event count within the AOI greater than magnitude -1 is equal to or more than 30 and less than 40.
 - During Advisory alert level, daily microseismic data processing is performed on business days.
 - A weekly report is provided to LDNR IMD with a summary of microseismic activity in the AOI for the previous week’s microseismic activity.
 - The Advisory Alert level remains active until seismic levels reach “Low” level for 1 day and the alert level is lowered back to GREEN.
- **Watch Level (ORANGE)** alert level is considered an increased level of microseismicity at the Sulphur Mines salt dome and is defined below.
 - Watch level is defined when microseismic events equal to or less than magnitude 1.0 but less than magnitude 1.5 occur within the AOI and/or;
 - Daily event count within the AOI greater than magnitude -1 is equal to or more than 40 and less than 50.
 - At the Watch level the microseismic data is processed seven days per week.
 - The microseismic activity within the AOI is reported to the LDNR IMD twice a week for the previous time period. Emails and text messages are used to provide notification of magnitude thresholds and event counts for the twice weekly report.
 - The Watch Alert status remains active until seismic levels reach a lower level (Low or Advisory Levels) for two consecutive days.
- **Warning Level (RED)** alert level is considered the highest alert level at Sulphur Mines dome and is defined below.
 - Warning level is defined when an event magnitude is equal to or exceed magnitude 1.5 in the AOI.
 - Daily event count within the AOI greater than magnitude -1 is equal to or greater than 50.
 - At the Warning level, the microseismic data is processed 7 days per week.
 - A daily report is provided to LDNR IMD for the previous day’s activity within the AOI, and online meetings with stake holders are scheduled as needed. Emails and text messages to stakeholders are used to provide notification as needed.
 - The Warning level status remains active until seismicity levels within the AOI reach lower status level (orange, yellow or green) for two consecutive days.

Table 1. Proposed initial Microseismic Alert System for Sulphur Mines Salt Dome outlining the alert level, criteria and response. Changes to the alert levels are provided within 24 hours on Monday-Friday, business working days in France.

Alert Status	Criteria	Response
Low (GREEN)	No events with magnitude ≥ 0.5 in AOI and/or Less than 30 MEQ per day in AOI with magnitudes ≥ -1	Once per week data processing, with previous monthly microseismic activity summary in the AOI is provided by the 15th of the following month to LDNR IMD.
Advisory (YELLOW)	Event with magnitude ≥ 0.5 and < 1.0 in AOI and/or Count of MEQ per day ≥ 30 and < 40 in AOI with magnitudes ≥ -1	Daily data processing M-F. Weekly reporting is provided LDNR IMD with activity summary from the previous week. Status remains active until seismic levels within the AOI reach "low"(green) level for 1 day.
Watch (ORANGE)	Event with magnitude ≥ 1 and < 1.5 in AOI and/or Count of MEQ ≥ 40 and < 50 with magnitudes ≥ -1 in AOI	Seven days per week data processing, 2x week reporting with activity for the previous days is provided via email and text message notifications to IMD. Status remains active until seismic levels within the AOI reach Advisory or Low criteria for 2 consecutive days.
Warning (RED)	Event with magnitude ≥ 1.5 in the AOI and/or Count of MEQ ≥ 50 with magnitudes ≥ -1 in the AOI	Seven days per week data processing, daily reporting with online meetings with stake holders as needed. The warning status level remains active until seismicity levels within the AOI reach a lower status level for 2 consecutive days.

Comments. The proposed Microseismic Alert System is considered an initial set of definitions that will likely need to be modified over time as microseismic data pertinent to Sulphur Mines dome is collected. Additional data such as cavern pressures, deformation measurements InSAR, GPS and a tiltmeter array around the Sulphur Mines dome is expected to assist in the salt dome monitoring to for potential hazards.

Appendix 1.

Table 2. Corner coordinates of the proposed AOI for Sulphur Mines Dome Microseismic Alert System.

Corner	WGS84	
	Latitude	Longitude
AOI NW	30.255562	-93.419456
AOI NE	30.255562	-93.410710
AOI SE	30.250098	-93.410710
AOI SW	30.250098	-93.419456

Table 3. Holiday Schedule in France for 2024.

Holidays and Observances in France in 2024

Date		Name
Jan 1	Monday	New Year's Day
Apr 1	Monday	Easter Monday
May 1	Wednesday	Labor Day / May Day
May 8	Wednesday	WWII Victory Day
May 9	Thursday	Ascension Day
May 20	Monday	Whit Monday
Jul 14	Sunday	Bastille Day
Aug 15	Thursday	Assumption of Mary
Nov 1	Friday	All Saints' Day
Nov 11	Monday	Armistice Day
Dec 25	Wednesday	Christmas Day

References

Ellsworth, B., S. Horton, H. Benz, B. Chouet, P. Dawson, S. Hickman, A. Leeds, B. Leith, M. Meremonte, J. Rubinstein, D. Shelly, M. Withers and B. Herrmann, 2012, Tremors in the Bayou: The Events on the Napoleonville Salt Dome, Louisiana, Abstract S51E-2453 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-7 December 2012.

Nayak, A., PhD Thesis, University of California, Berkeley, I. Seismic Moment Tensor Analysis of Micro-Earthquakes in an Evolving Fluid-Dominated System and II. Ambient Noise Cross-Correlation for Evaluating Velocity Structure and Instrument Orientations in a Geothermal Environment (Fall 2017)

Shemeta, J., "Borehole Microseismic Monitoring at Napoleonville Salt Dome, Louisiana: Nine Years of Microseismicity Associated with Brining and Storage Facilities on a Gulf Coast Salt Dome, USA", SMRI Spring Technical Conference 24-25 April 2023, Detroit Michigan, USA.

Shemeta, J. Surface Seismic Monitoring Report Sulphur Mines Dome Broadband Seismic Array, Report period April 1-15, 2024, report to Louisiana Department of Natural Resources, IMD. April 16, 2024 (a).

Shemeta, J., Microseismic Monitoring Report Sulphur Mines Salt Dome Borehole Seismic Arrays, Report Period April 21 – May 31, 2024, report to Louisiana Department of Natural Resources, IMD. June 5, 2024(b).