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Surface Seismic Monitoring Report
Sulphur Mines Salt Dome Broadband Seismic Array

Report Period : December 16-31, 2023

Report Date: January 2, 2023

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Using results from Nanometrics

Summary

- One microseismic location was reported from December 16-31, 2023, a magnitude -0.73 event located near an active drilling location for the MW-2 monitor well.
- All five broadband stations were operational from December 16-31, 2023.

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 December 16-31, 2023.

The broadband station locations are show in Figure 1 and listed in Table 1. Figure 2 shows the broadband network amplitude over time from December 16-31, 2023 (background noise plot). The background noise is similar to the previous reporting, the noisiest station is SUL01, followed by SUL02 and the quietest stations in this time period were stations SUL03 and SUL05.

As mentioned in the previous report, the plan for the seismic network is to move station SUL01 approximately 2400 feet to the WNW (Figure 1, labeled SUL01 Trillium NEW LOC) and add an additional station to the west of the dome, SUL06 (labeled "SUL06 PROPOSED TRILLIUM"). The station moves will likely occur sometime in Q1 2024.

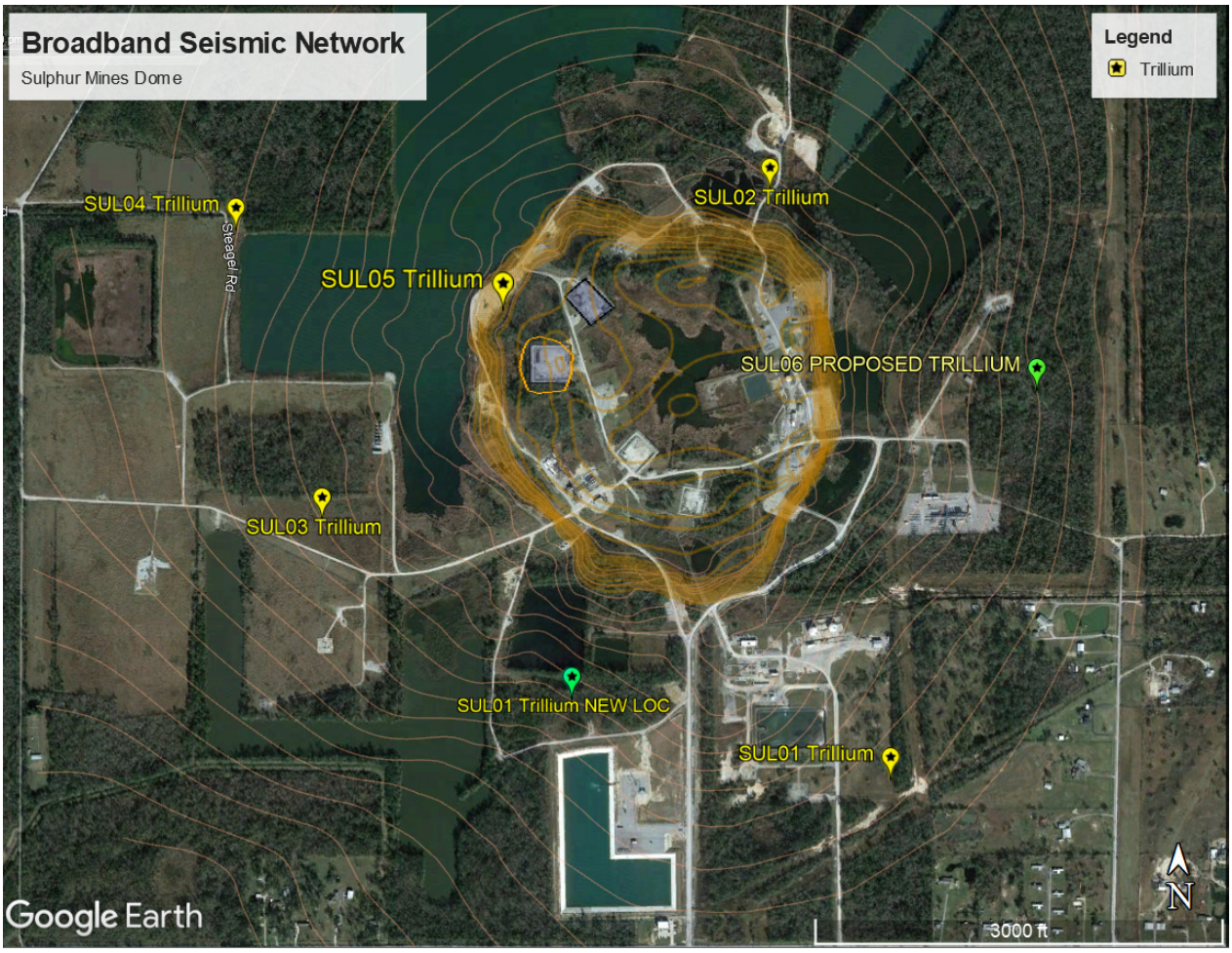


Figure 1. Google Earth map image showing the location of the broadband seismic (Trillium Compact Sensors, yellow symbols and labels) stations near and at the Sulphur Mines Salt Dome. The contours are the salt and cap rock elevations, the orange circle is the general outline of Cavern 7. Two new stations are shown in green symbols, SUL01 Trillium NEW LOC is the proposed approximate location for moving SUL01, and a new station SUL06 PROPOSED TRILLIUM is the approximate location for a new seismic station.

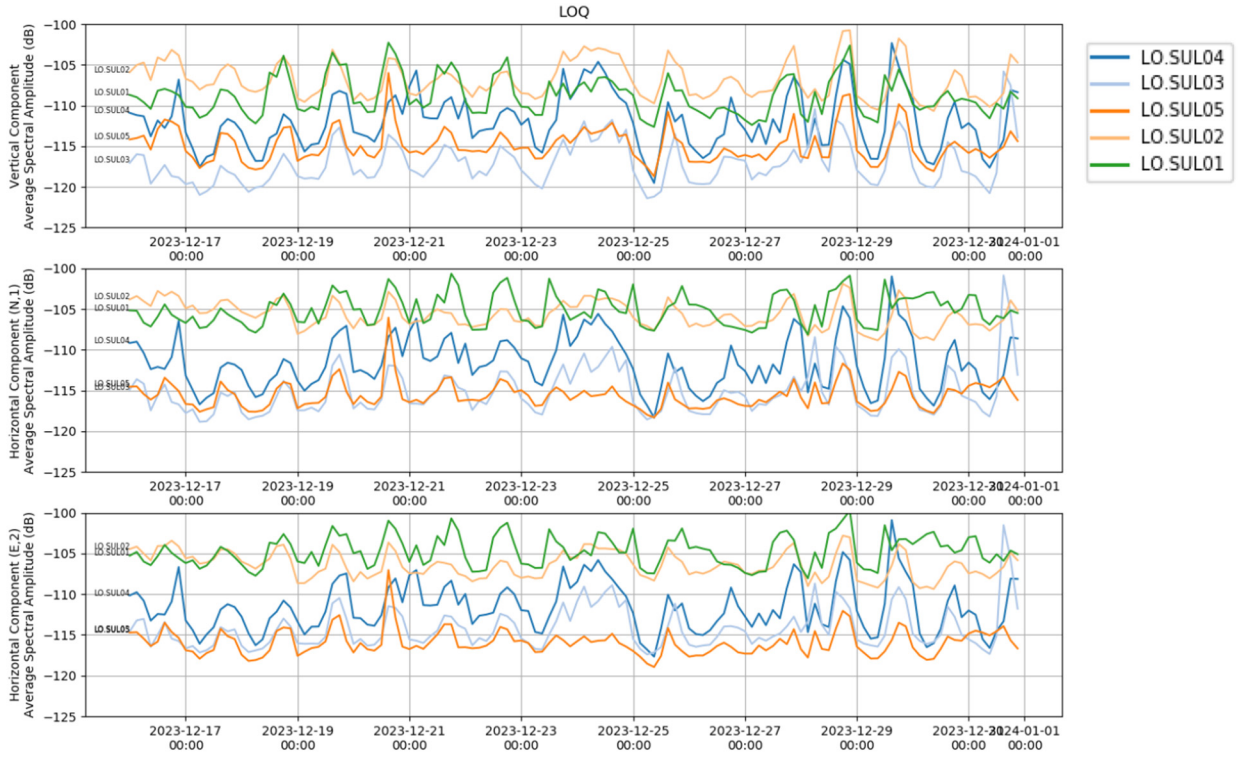


Figure 2. Average spectral amplitudes in decibels on the five broadband sensor from December 16-31, 2023. The upper plot is the vertical component, the middle and lower plots are the horizontal component (middle is north-south and lower plot is east-west component).

December 20 Event location.

A magnitude -0.73 seismic event occurred on December 20, 2023 @7:04:29 PM central, with a NAD27 LA South St Plane location in feet, X= 1,343,300.63, Y= 582,051.49, Z=558 msl (Figure 3).

The magnitude was computed using an attenuation (Q) value of 200. Using three other Q values from high to low attenuation are listed below. Q = 100 is the highest attenuation value (note Q is inversely proportional to attenuation, smaller numbers have higher attenuation). The magnitude is estimated from the low-frequency content of the seismic waveform; hence the magnitude values are less affected by attenuation.

Q	Magnitude
100	-0.69
150	-0.71
200	-0.73

The event was in close proximity in location and timing to the actively drilling MW-2 water monitor well. The MW-2 was drilled December 15-18, 2023. Total depth of the well was reached on Dec. 18, about 800 ft below KB.

The drilling log is as follows (as per Scott Himes, ERM):

Dec 19 – No active drilling, hole was cleaned out, and loggers arrived to log the hole. Approximately 1 pm the logging tool became stuck in the hole at the bottom of the casing (~150' deep). There was a lot of pulling trying to free to tool. The cable broke and the tool fell to the bottom of the hole at approximately 3 pm.

Dec 20 – No active drilling. Fishing tools arrived on site about 7:30 am. Fishing began about 10 am. Tool was removed about 2 pm. No other activities occurred at the drill location.

Dec 21 – No active drilling, hole was cleaned out, and logging was completed.

Given the close proximity and timing of the event and the MW-2 monitor well, it appears the Dec. 20 microseismic event was likely an induced event associated with the drilling of the well. The drilling process may have induced the event by increasing the pore pressure in the vicinity of the wellbore. Seismicity associated with drilling process has been observed in Iceland and Brazil geothermal projects (Augstsson et al., 2015, Yamabe and Hamaz, 1996). A critically-stressed, preexisting fracture near the wellbore with geometry favorable for slip was likely activated. Another possibility is the small stress changes due to drilling process induced the microseismic event.

The small magnitude of the December 20 event suggests the amount of slip is likely less than 1 mm. The event location illustrates the broadband seismic array is actively recording seismicity and the accuracy of the locations is quite high.

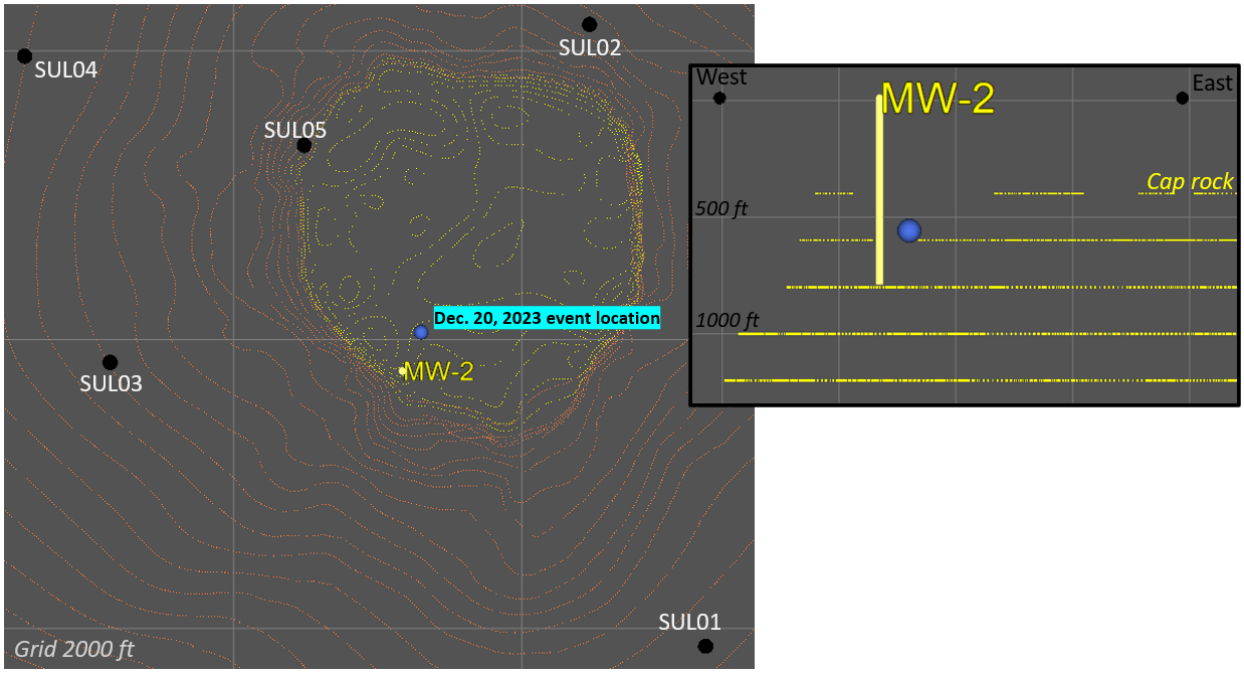


Figure 3. Map (left) and east-west cross section (right) of December 20, 2023 event location and the MW-2 monitor wellbore. Yellow dots are the cap rock and orange are salt. Surface seismic instruments are show by black dots and are labeled in map view.

Magnitude Detectability. 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).

References

Ágústsson, K., Kristjánsdóttir, S., Flóvenz, Ó. G., & Gudmundsson, O. (2015). Induced seismic activity during drilling of injection wells at the Hellisheidi power plant, SW Iceland. In "*Proceedings World Geothermal Congress 2015"*.

Yamabe, T. H. and Hamza, V. M., "Geothermal investigations in an area of induced seismic activity, northern São Paulo State, Brazil", *Tectonophysics*, Volume 253, Issues 3–4, 1996, Pages 209-225, ISSN 0040-1951, https://doi.org/10.1016/0040-1951(95)00055-0.

Appendix 1. Seismic Station Locations

Table 1. Seismic Station locations and operational dates at Sulphur Mines Dome (to December 31, 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 3). 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 3).

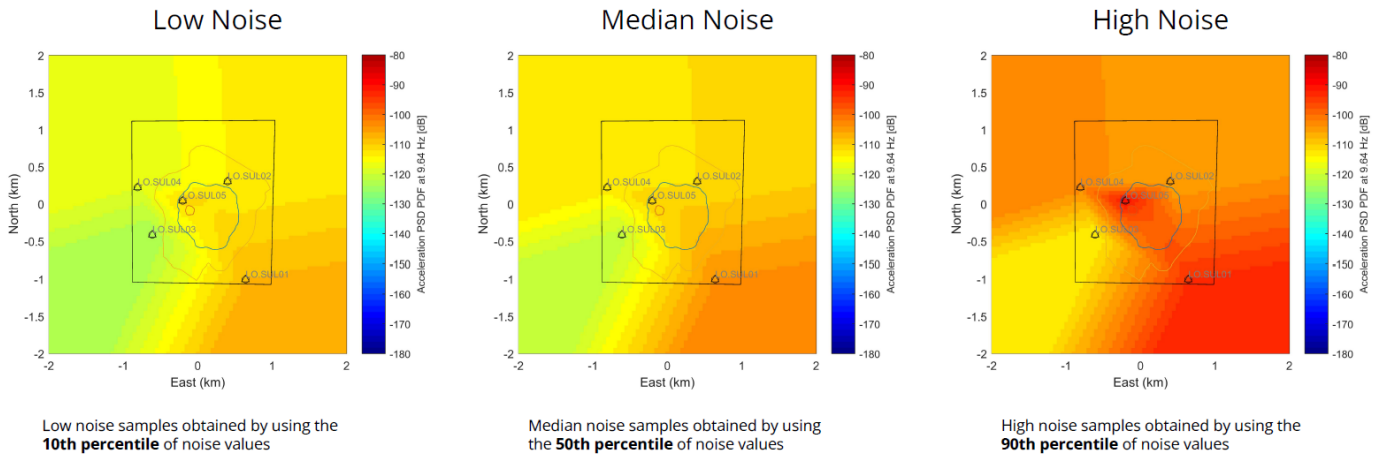


Figure 3. Map of the noise levels modeled for the magnitude of completeness figures. Left most is the low noise, middle median noise and right is high noise.

The map of the magnitude of completeness modeled by Nanometrics for the three noise levels is shown in Figure 4 for the Sulphur Mines dome area. The Mc will vary spatially (Figure 4) depending on the station geometry and the event location and depth.

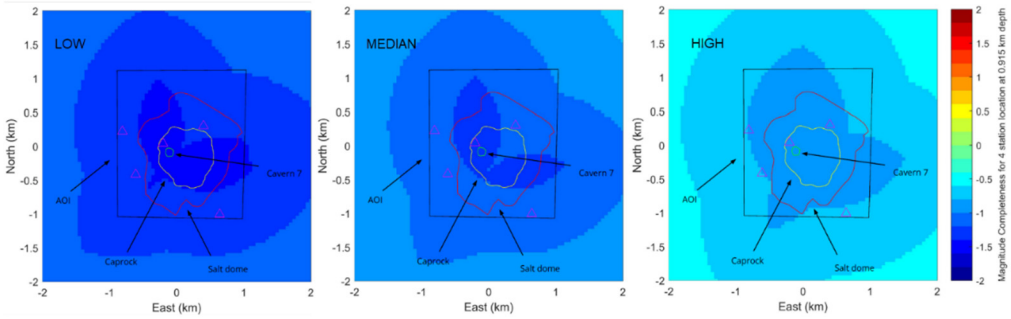
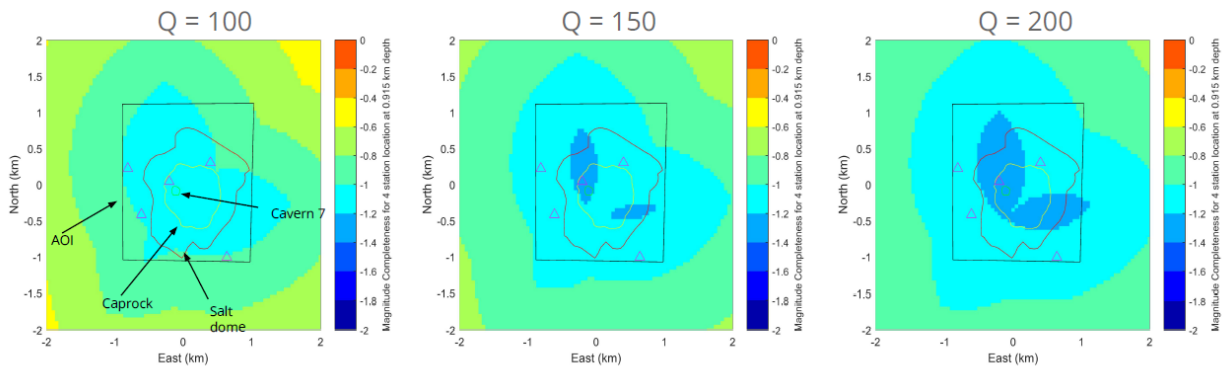


Figure 4. Modeled magnitude of completeness (Mc, lowest magnitude detectable) for the Sulphur Mines salt dome and vicinity using the broadband array. Three noise models are shown: the high noise model shown on the right, median noise level in the middle and low noise model on the left, as labeled. The 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 5 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 5. 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=200,(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.