Title
EGS Collab Experiment 2: Continuous Active Source Seismic Monitoring (CASSM) system

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Contents

1 Terminology

- **SURF**: Sanford Underground Research Facility. The old Homestake gold mine in Lead, SD, USA where the EGS Collab experiment has taken place.
- **OD**: Outer diameter
- **ERT**: Electrical Resistivity Tomography
- **CASSM**: Continuous Active Source Seismic Monitoring. A network of piezoelectric sources and seismic receivers for cross-well seismic tomography.
- **LBNL or LBL**: Lawrence Berkeley National Lab (Berkeley, CA)
- **SNL**: Sandia National Lab (Albuquerque, NM)
- **PNNL**: Pacific Northwest National Lab (Richland, WA)

2 Introduction

The EGS Collab Experiment #2 took place from approximately February–September 2022 at the Sanford Underground Research Facility in Lead, SD. The project was the continuation of a years-long experiment aiming to validate models of enhanced geothermal systems through a series of high-pressure injections into rock between 1200 and 1500 meters below the surface. These injection experiments were extensively monitored by a number of systems including seismic waveform recording, pressure and temperature probes, active source seismic tomography, electrical resistivity tomography, and a full suite of distributed fiber optic interrogators.

This report details the active source seismic monitoring system that conducted a continuous cross-well seismic survey throughout the experiment. This monitoring system consisted of accelerometers and hydrophones placed in various boreholes surrounding the injection zones. These sensors recorded the signals generated by piezoceramic sources that were also installed in the boreholes.

3 Installation

The seismic monitoring system for EGS Collab Experiment 2 consisted of two types of seismic sensors: piezoelectric accelerometers and hydrophones. These sensors were recorded by two different recording systems each targeting a different application. One recording system recorded 64-channels of data continuously for the purpose of monitoring for seismicity that was induced and/or triggered by the injection operations. These data were processed in real-time in an attempt to monitor seismicity to inform decision-making during the experiment. The other recording system recorded the same sensors only at a lower sampling rate and in triggered mode. This system was a part of an active-source monitoring system called CASSM (Continuous Active-Source Seismic Monitoring) that uses waves emitted from custom-built piezoelectric sources installed in the boreholes to estimate various properties of the rock volume with time. While the sensors are common across both systems, this report focuses on the CASSM recording system.

3.1 Sensors

The piezoelectric accelerometers were manufactured by MMF of Germany. They are model KS943B100 triaxial sensors that conform to the IEPE (Integrated Electronics Piezo Electric) standard. They have a sensitivity of 100 mV/g (the sensors installed on the 4850 level for EGS Collab Experiment 1 had a sensitivity of 1 V/g) and a linear frequency response range of 0.5 Hz to 22 kHz within 3 dB. The full specsheet can be found here. Each of the 16 MMF accelerometers was packaged into a stainless steel housing at the Geosciences Measurement Facility (GMF) at LBNL (Figure 4A and B). Calibration certificates for three of these accelerometers were purchased and are included in the GDR submission for the continuous waveform data. For analyses requiring correction of the data to real units (i.e. sensor frequency response removal) the user is directed to these certificates that can be used to construct sensor response files. While some minor discrepancies exist between sensors, we feel it is reasonable to treat all sensors as having a response curve equivalent to the average of these three calibration curves.

A string of 24 hydrophones was installed in one of the open boreholes, TS (water-coupled; not grouted). This string consisted of HTI-96-MIN/V 5/8 sensors manufactured by High Tech, Inc. The hydrophones have a flat frequency response from 2 Hz to 2 kHz. Due to a misunderstanding in the ordering process, a 2 kHz hardware lowpass-filter was installed in the preamplifier. This means that much of the anticipated frequency content of the seismicity for this experiment (into the 10s of kHz) was not recorded on these instruments. The array had an inter-sensor spacing of 2.5 m.

Finally, 20 active seismic sources were installed. These sources are cylindrical piezoelectric crystals manufactured at the Geosciences Measurement Facility at LBNL. Sources are fired by applying a voltage across the thickness of the piezoelectric ceramic and the signal is recorded across the array of sensors described above. This system is known as Continuous

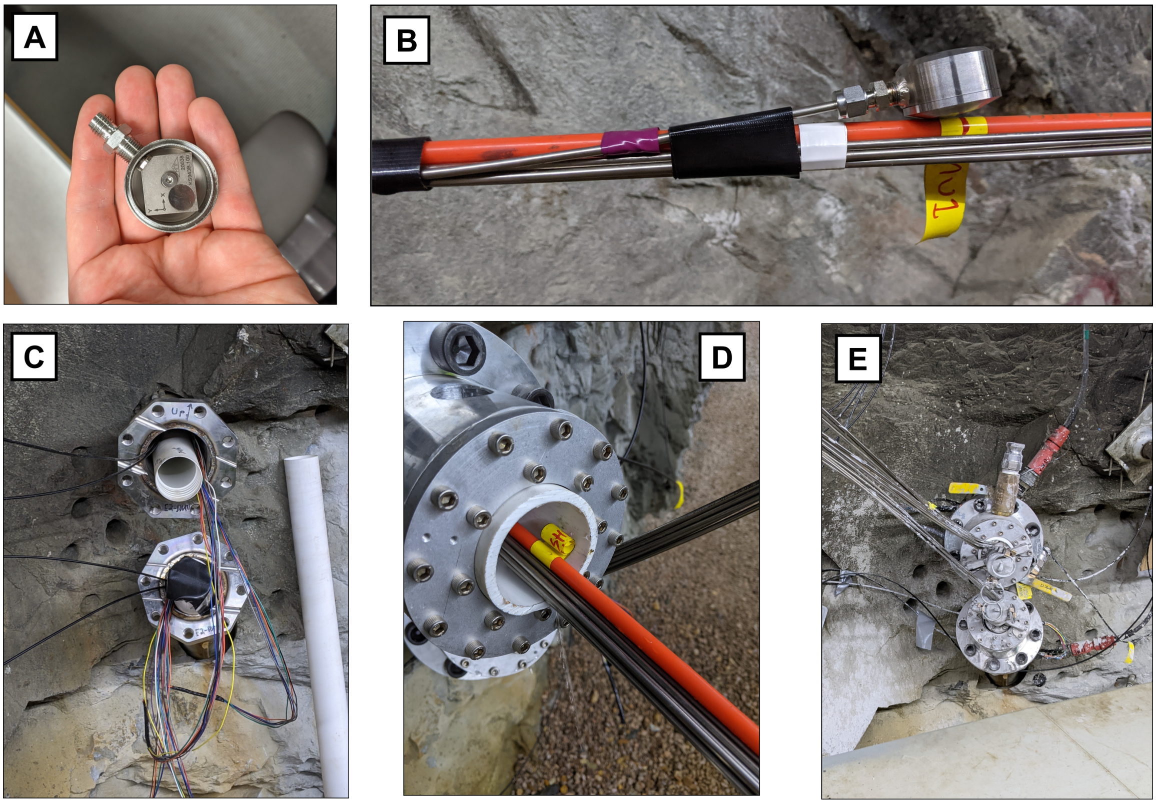


Figure 1: Pictures of the various stages of accelerometer fabrication and installation. A) A single triaxial accelerometer inside an open steel housing B) Completed housing attached to TEC and taped to a conveyance rod (orange fiberglass). C) Schedule 40 PVC shrouds protruding from the wellheads. These were necessary to isolate the ERT electrodes from all of the metal involved in the wiring and housings for the seismic sensors. D) The wellheads were sealed off using a custom machined cap from SNL that left the inside of the shroud open to lower the seismic sensor package E) Final state of the fully grouted boreholes DMU and DML with all sensor cables fed through the wellcaps.

Active Source Seismic Monitoring or CASSM [1].

To protect the conductors as they ran up the grouted boreholes, stainless steel tubing encapsulated cable (TEC) was used. This choice was made mostly to avoid fluid infiltrating the CASSM sources and accelerometers, which damaged a number of sensors in Experiment #1 on the 4850 level of the mine.

3.2 Borehole array design

Each of the monitoring array boreholes needed to fit many different sets of sensing equipment, each with unique requirements. This equipment included not only the seismic sensors and their cables, but also a steel encased fiber optics package and also a number of electrodes for the electrical resistivity tomography (ERT) system. One major consideration was that any metal in the borehole would severely interfere with the ERT system and would therefore need to be electrically isolated. This was done by placing all of the seismic instrumentation inside a 2.5-inch schedule 40 PVC "shroud". The ERT electrodes were strapped to the outside of the shroud along with the fiber optic package (which was steel encapsulated but coated in a non-conductive material). The one non-grouted monitoring borehole, TS, was designed in a similar way, with the exception being that it contained no steel cables for the CASSM sources or the hydrophone string (they were plastic coated instead). Cross sections for both grouted and non-grouted boreholes are shown in Appendix 6.4.

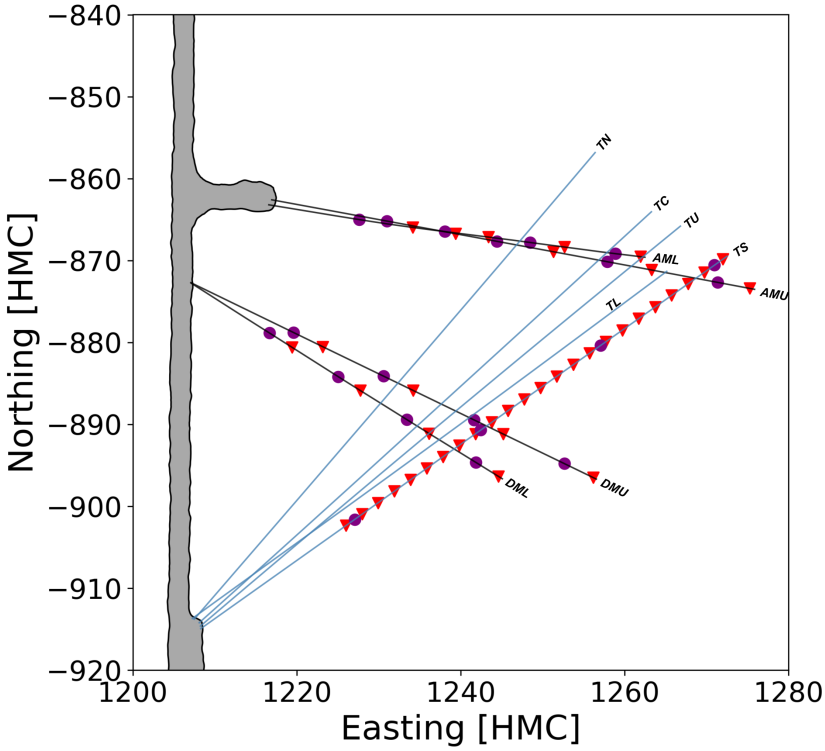
3.3 Array layout

Figure 2 shows the geometry of the seismic array with grouted boreholes shown in black, open boreholes shown in blue, and seismic sensors shown as red inverted triangles.

Each of the grouted boreholes contained four CASSM sources and four three-component accelerometers. The spacing and location of these instruments were chosen to maximize the ability of the accelerometers to constrain the location and mechanism of detected seismicity as well as to maximize the raypath coverage of the CASSM system. In borehole TS, four CASSM sources were installed alongside the 24-channel hydrophone array. The locations for each sensor are given in Table 3 within the Homestake Mine Coordinate system. This is a cartesian system used for most data coming out of the mine. Units are given in feet.

3.4 Recording systems

Two recording systems were used to digitize the data coming from the accelerometers and hydrophones; one in continous recording mode and the other in triggered recording



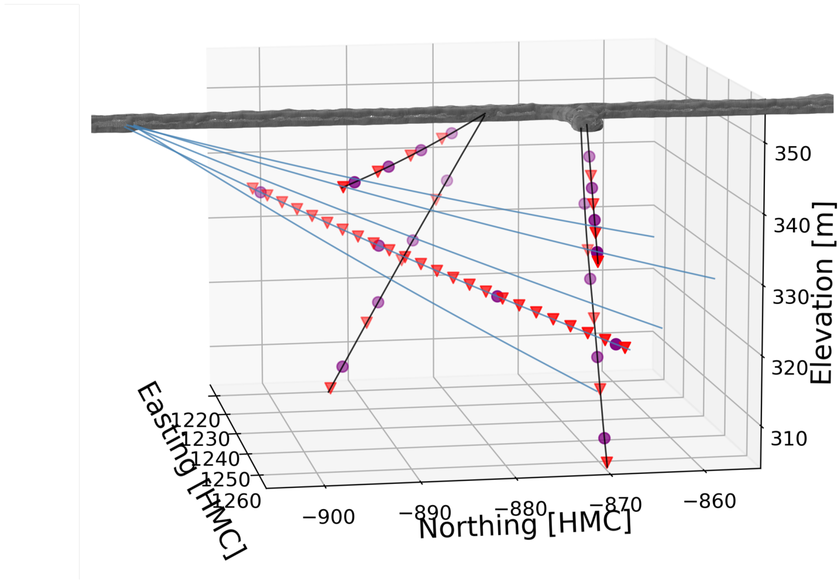


Figure 2: Overview of the EGS Collab Experiment 2 testbed on the 4100 level of SURF. The boreholes are labeled by name and the locations of the seismic sensors are indicated with red triangles. CASSM sources are shown as purple circles. The fiber loop is installed in the four grouted boreholes (AMU, AML, DMU, and DML) shown in black. A string of hydrophones is installed in non-grouted borehole TS.

mode. The continuous data recorder was a 64-channel VIBbox-64 manufactured by Data Translation. This system recorded each channel of the three-component accelerometers and half of the hydrophone channels at a sampling rate of 100 kHz. The triggered system was an interconnected series of four Geometrics Geode seismographs, which were triggered to record based on the shot times of the CASSM sources. This system recorded each available channel from all sensors. The continuous recording system is explained in greater detail in a separate submission to the Geothermal Data Repository.

3.5 Active source survey design

The active source survey ran continuously throughout the experiment. Each of the 20 sources was selected sequentially and fired 16 times before moving to the next. Shots occurred at a rate of roughly one per second. Once 16 shots occurred at a single source, the system stacked the recorded waveforms into a single file and saved it to disk. We refer to a single pass through all 20 sources (16 shots each) as an "epoch".

To generate a single shot, the CASSM control computer produced a 1-millisecond square wave that was then amplified to ± 300 V and applied across a single source (selected by a computer-controlled switch).

4 Data

This section describes the raw data and data products produced by the Geometrics Geode recording system. The continuous recordings from the Vibbox system are detailed in a separate report within the relevant GDR submission for the passive seismic dataset.

4.1 Raw data

The data from the four interconnected Geometrics Geodes were saved as SEG-2 files. The data are organized into single directories for each epoch of the survey, where an epoch comprises a single pass through each of the 20 sources. Within each epoch directory are 20 data files, one for each 16-shot stack of a single source. The files are numbered with the lowest number corresponding to the first source in the sequence and the highest to the last. The appendices include a table (Table 2) that indicates the CASSM source firing sequence. There is also a log file that contains information from the Geode recording system. These log files are somewhat polluted with metadata from previous phases of the experiment, so users who attempt to interpret them should contact the authors first.

4.2 Sensor calibration and frequency response information

As mentioned briefly above, we purchased calibration certificates for three of the 16 installed accelerometers. These certificates provide detailed information about the response of the sensors to excitation at known frequencies and can therefore be used to construct frequency response curves. These certificates are included in the GDR submission with the VIBbox dataset and Figure 3 shows the acceleration amplitude and phase response from these calibrations. The shake tests were only conducted up to 20 kHz, so users are cautioned against correcting for instrument response at frequencies higher than this. These results apply only to the bare accelerometers themselves and do not account for the effect of the enclosures or the grouting on the frequency response convolved into the data.

To help combat the unknowns mentioned above, we conducted a series of calibration shots along the rib of the main drift. Please see the report on the passive seismic recording system for more details on this survey. Analyses of these shots must be conducted manually using the continuous VIBbox data.

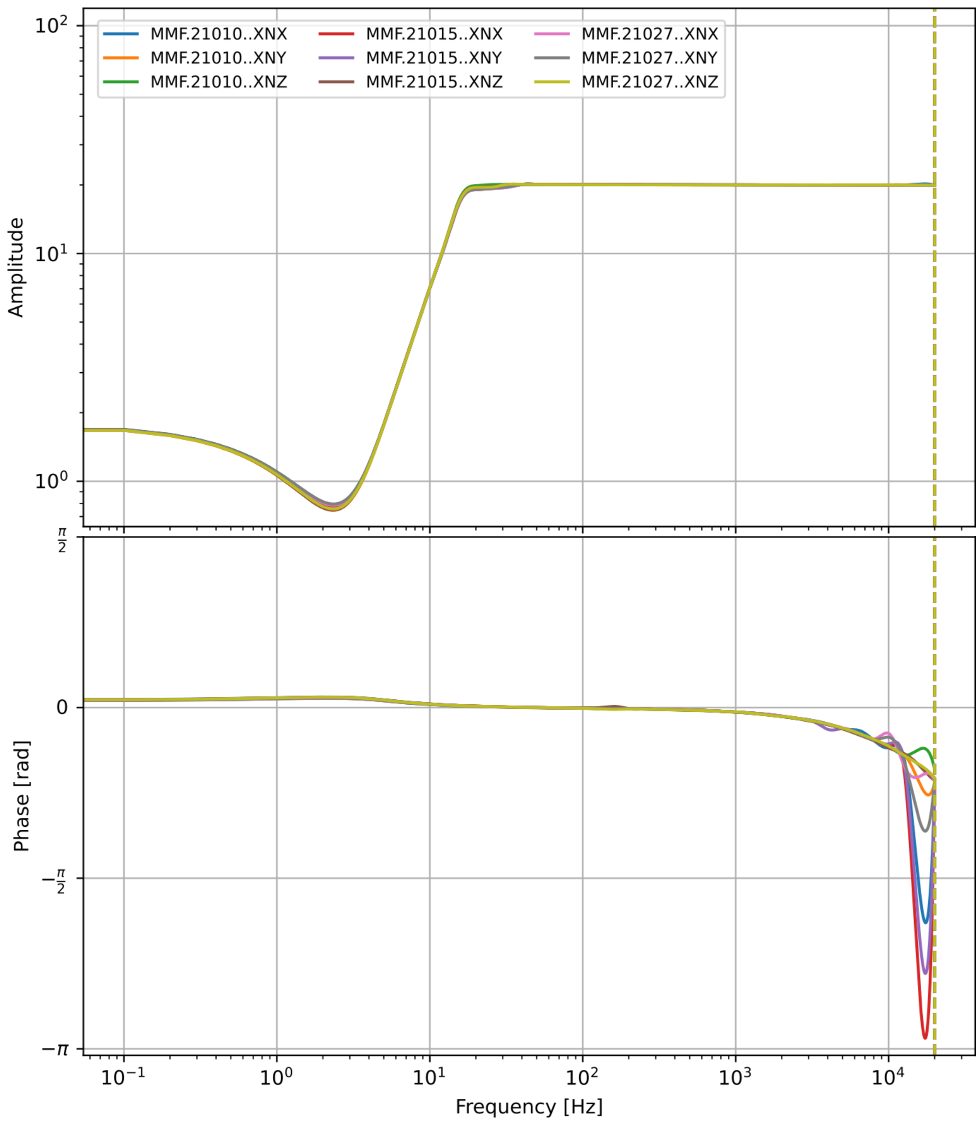


Figure 3: Acceleration amplitude (top) and phase (bottom) response for three of the 16 installed accelerometers. These results were obtained from a calibration certification process conducted by the sensor manufacturer MMF through a shake table test.

5 Results

At the time of writing (Jan 8, 2023), little analysis has been conducted on the CASSM data from EGS Collab Experiments 2 and 3. Please feel free to use this dataset as you please, but consider that a significant effort went into installing and maintaining this testbed as well as making these data available. If you plan to publish on these data, please cite the dataset (at a minimum) and reach out to the authors of this report.

6 Appendices

6.1 Geode channel order

SEED id	Type of data
CB.AML1..XNX	Accelerometer
CB.AML1..XNY	Accelerometer
CB.AML1..XNZ	Accelerometer
CB.AML2..XNX	Accelerometer
CB.AML2..XNY	Accelerometer
CB.AML2..XNZ	Accelerometer
CB.AML3..XNX	Accelerometer
CB.AML3..XNY	Accelerometer
CB.AML3..XNZ	Accelerometer
CB.AML4..XNX	Accelerometer
CB.AML4..XNY	Accelerometer
CB.AML4..XNZ	Accelerometer
CB.AMU1..XNX	Accelerometer
CB.AMU1..XNY	Accelerometer
CB.AMU1..XNZ	Accelerometer
CB.AMU2..XNX	Accelerometer
CB.AMU2..XNY	Accelerometer
CB.AMU2..XNZ	Accelerometer
CB.AMU3..XNX	Accelerometer
CB.AMU3..XNY	Accelerometer
CB.AMU3..XNZ	Accelerometer
CB.AMU4..XNX	Accelerometer
CB.AMU4..XNY	Accelerometer
CB.AMU4..XNZ	Accelerometer
CB.DML1..XNX	Accelerometer
CB.DML1..XNY	Accelerometer
CB.DML1..XNZ	Accelerometer
CB.DML2..XNX	Accelerometer
CB.DML2..XNY	Accelerometer
CB.DML2..XNZ	Accelerometer
CB.DML3..XNX	Accelerometer
CB.DML3..XNY	Accelerometer
CB.DML3..XNZ	Accelerometer
CB.DML4..XNX	Accelerometer
CB.DML4..XNY	Accelerometer
CB.DML4..XNZ	Accelerometer
CB.DMU1..XNX	Accelerometer
CB.DMU1..XNY	Accelerometer

CB.DMU1..XNZ	Accelerometer
CB.DMU2..XNX	Accelerometer
CB.DMU2..XNY	Accelerometer
CB.DMU2..XNZ	Accelerometer
CB.DMU3..XNX	Accelerometer
CB.DMU3..XNY	Accelerometer
CB.DMU3..XNZ	Accelerometer
CB.DMU4..XNX	Accelerometer
CB.DMU4..XNY	Accelerometer
CB.DMU4..XNZ	Accelerometer
CB.TS24..XDH	Hydrophone
CB.TS23..XDH	Hydrophone
CB.TS22..XDH	Hydrophone
CB.TS21..XDH	Hydrophone
CB.TS20..XDH	Hydrophone
CB.TS19..XDH	Hydrophone
CB.TS18..XDH	Hydrophone
CB.TS17..XDH	Hydrophone
CB.TS16..XDH	Hydrophone
CB.TS15..XDH	Hydrophone
CB.TS14..XDH	Hydrophone
CB.TS13..XDH	Hydrophone
CB.TS12..XDH	Hydrophone
CB.TS11..XDH	Hydrophone
CB.TS10..XDH	Hydrophone
CB.TS09..XDH	Hydrophone
CB.TS08..XDH	Hydrophone
CB.TS07..XDH	Hydrophone
CB.TS06..XDH	Hydrophone
CB.TS05..XDH	Hydrophone
CB.TS04..XDH	Hydrophone
CB.TS03..XDH	Hydrophone
CB.TS02..XDH	Hydrophone
CB.TS01..XDH	Hydrophone
CB.PPS..	Pulse per second time signal
CB.CEnc..	CASSM Source Encoder
CB.CMon..	CASSM Monitor
CB.CTrig..	CASSM Trigger

Table 1: SEED names for each channel in the order stored in the geode SEG-2 data files.

6.2 Seismic source firing sequence

Sequence no.	Station name	X [HMC ft]	Y [HMC ft]	Z [HMC ft]
1	AMLS1	4027.62	-2837.96	1094.47
2	AMLS2	4061.82	-2842.75	1065.22
3	AMLS3	4096.00	-2847.12	1036.05
4	AMLS4	4130.12	-2851.59	1007.06
5	AMUS1	4038.72	-2838.55	1120.23
6	AMUS2	4082.78	-2846.65	1114.25
7	AMUS3	4126.92	-2854.83	1108.93
8	AMUS4	4171.02	-2863.09	1104.45
9	DMLS1	3991.68	-2883.36	1100.20
10	DMLS2	4019.22	-2900.86	1076.72
11	DMLS3	4046.68	-2918.06	1053.26
12	DMLS4	4074.29	-2935.17	1029.75
13	DMUS1	4001.34	-2883.20	1126.07
14	DMUS2	4037.33	-2900.63	1125.26
15	DMUS3	4073.61	-2918.18	1125.20
16	DMUS4	4109.70	-2935.66	1125.90
17	TSS1	4025.78	-2958.02	1104.28
18	TSS2	4076.25	-2922.23	1088.06
19	TSS3	4124.30	-2888.31	1074.06
20	TSS4	4169.79	-2856.21	1062.08

Table 2: XYZ coordinates for each seismic source in the order they are fired during each epoch. The coordinates are in Homestake Mine Coordinates, which is a cartesian coordinate system used in the mine. Units are feet.

6.3 Seismic sensor locations

Station name	X [HMC ft]	Y [HMC ft]	Z [HMC ft]
TS01	4022.31	-2960.48	1105.46
TS02	4028.73	-2955.92	1103.28
TS03	4035.16	-2951.36	1101.13
TS04	4041.66	-2946.75	1098.99
TS05	4048.12	-2942.17	1096.89
TS06	4054.60	-2937.57	1094.81
TS07	4061.09	-2932.98	1092.76
TS08	4067.58	-2928.38	1090.73
TS09	4074.11	-2923.75	1088.72
TS10	4080.62	-2919.14	1086.73
TS11	4087.12	-2914.54	1084.77
TS12	4093.60	-2909.95	1082.84
TS13	4100.12	-2905.35	1080.92
TS14	4106.70	-2900.71	1079.01
TS15	4113.24	-2896.10	1077.15
TS16	4119.78	-2891.49	1075.32
TS17	4126.34	-2886.87	1073.50
TS18	4132.88	-2882.27	1071.72
TS19	4139.49	-2877.60	1069.93
TS20	4146.05	-2872.97	1068.19
TS21	4152.63	-2868.32	1066.46
TS22	4159.19	-2863.69	1064.76
TS23	4165.74	-2859.07	1063.10
TS24	4173.16	-2853.83	1061.23
AML1	4048.97	-2841.08	1076.23
AML2	4079.26	-2844.94	1050.32
AML3	4109.72	-2848.92	1024.38
AML4	4140.21	-2852.81	998.55
AMU1	4066.11	-2843.57	1116.46
AMU2	4105.28	-2850.81	1111.44
AMU3	4144.56	-2858.12	1107.05
AMU4	4183.85	-2865.50	1103.29
DML1	4000.66	-2889.07	1092.55
DML2	4028.11	-2906.44	1069.13
DML3	4055.58	-2923.61	1045.67
DML4	4083.34	-2940.78	1022.03
DMU1	4013.04	-2888.87	1125.73
DMU2	4049.22	-2906.38	1125.15
DMU3	4085.22	-2923.81	1125.34
DMU4	4121.21	-2941.24	1126.23

Table 3: XYZ coordinates for each seismic source and sensor. The coordinates are in Homestake Mine Coordinates, which is a cartesian coordinate system used in the mine. Units are feet.

6.4 Borehole design cross-sections

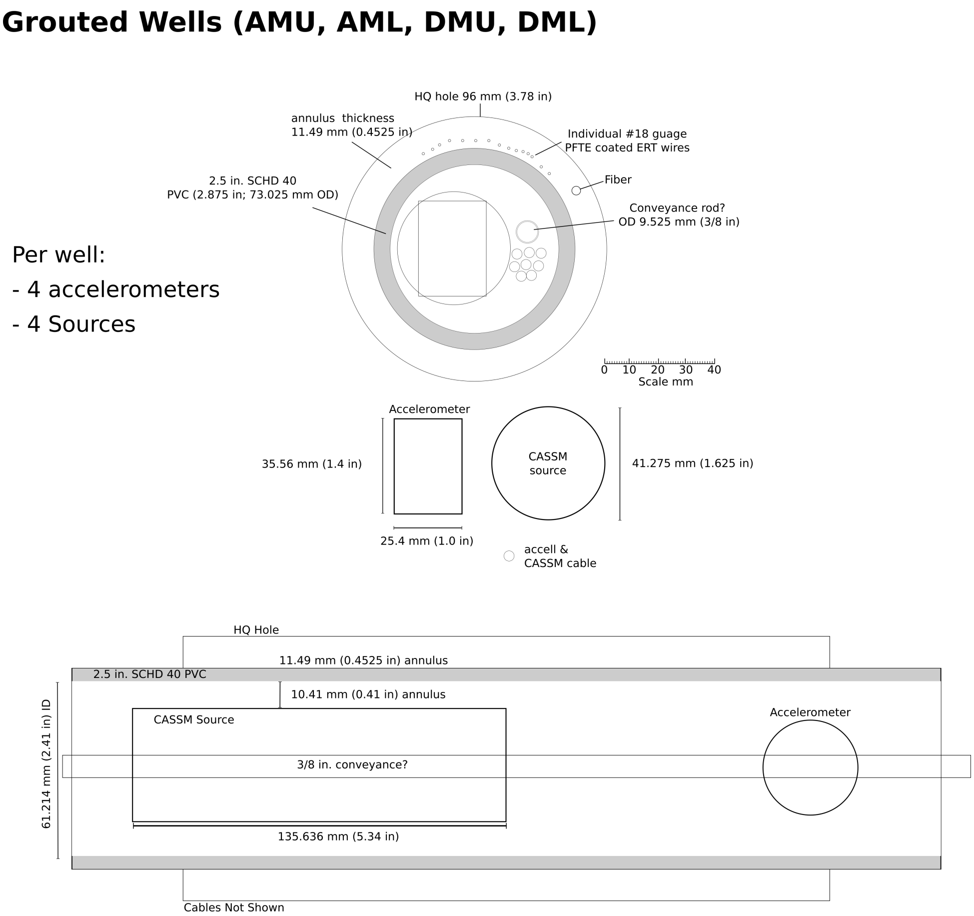


Figure 4: Scale cross-section of the grouted boreholes AMU, AML, DMU, DML showing all equipment installed in these boreholes.

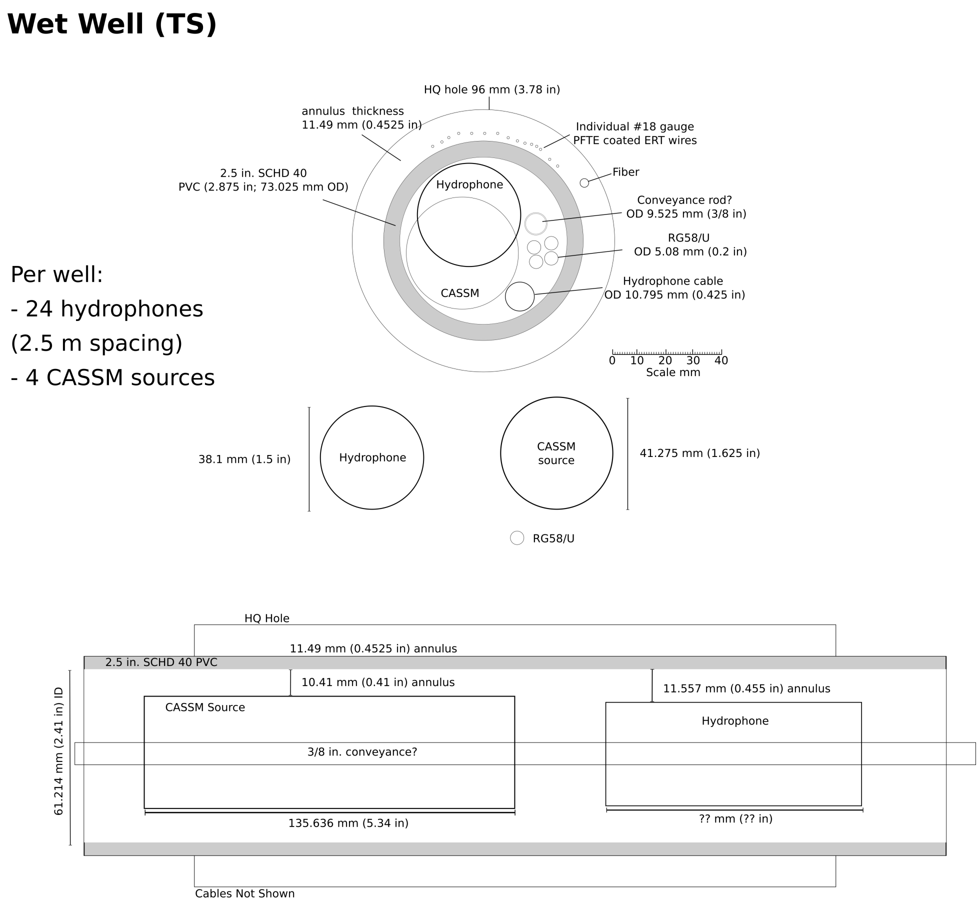


Figure 5: Scale cross-section of the non-grouted (i.e. wet) borehole, TS, showing all equipment installed.

References

[1] Thomas M. Daley, Ray D. Solbau, Jonathan B. Ajo-Franklin, and Sally M. Benson. Continuous active-source seismic monitoring of CO2 injection in a brine aquifer. *Geophysics*, 72(5):A57–A61, 07 2007.