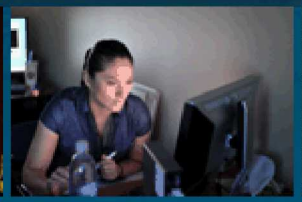
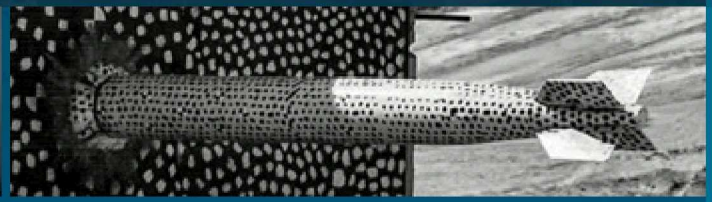
SAND2020-1708PE

Seismic and Infrasound Data Collection at Redmond Salt Mine, Central Utah





PRESENTED BY

Nathan Downey

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

Redmond Salt Mine Monitoring Experiment

- Experiment Setting and Procedures
- Analysis of Infrasound Signals Generated in Tunnels
- Assembly of a Ground-Truth Seismic Event Dataset
- Local Discrimination Dataset

Onboard Processing System

- Design of an Autonomous Seismic Analysis Platform
- Field Testing of Onboard Processing System

Motivation

Obtain Test Datasets for Algorithm Testing and Development

- Examination of existing datasets reveals few quality records of explosive events at stations with both seismic and infrasound instrumentation
- This lack of data is especially acute at local distances (<100km offset from source location to recording station)

Additional Features of Redmond Salt Mine

- Underground blasting occurs in a large tunnel complex (10's of miles of underground roads)
- The mine is located within a belt of active seismicity allowing easy comparison of natural and explosive sources

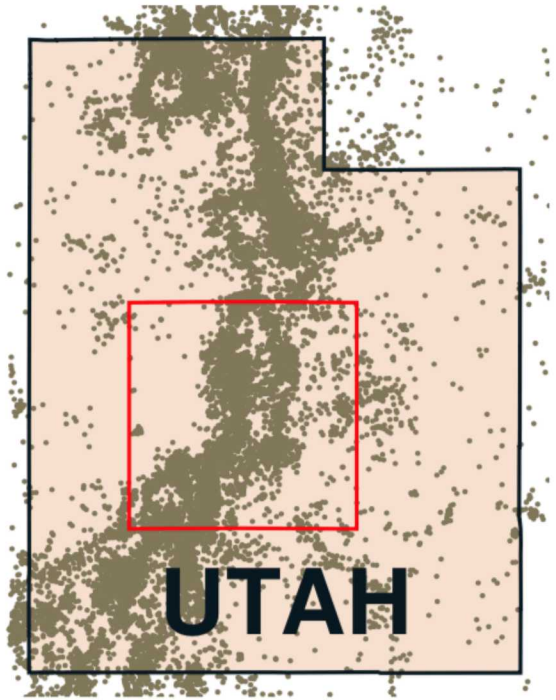
Goals

(1) Obtain a seismoacoustic dataset to be used in algorithm development

(2) Record local signatures of explosive events, natural earthquakes and mining-related events

(3) Devise method by which explosive events can be detected by University of Utah regional network

Seismotectonics of Central Utah

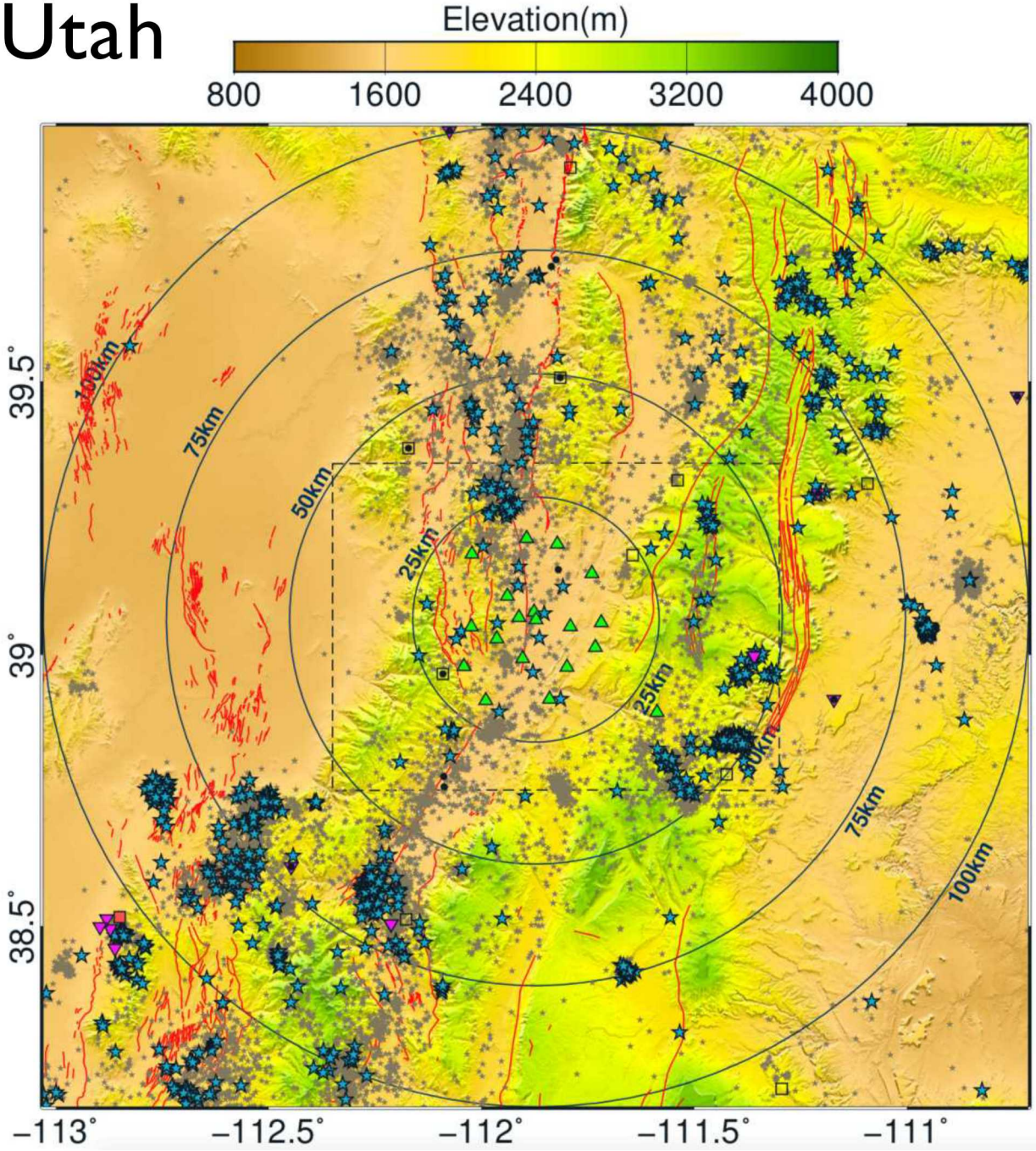


Symbols

- Quaternary Faults
- Contours of Distance to Mine
- Outline of Figure 2
- Earthquake Prior to 10/2017
- Earthquake 10/2017–09/2019

Seismic Stations

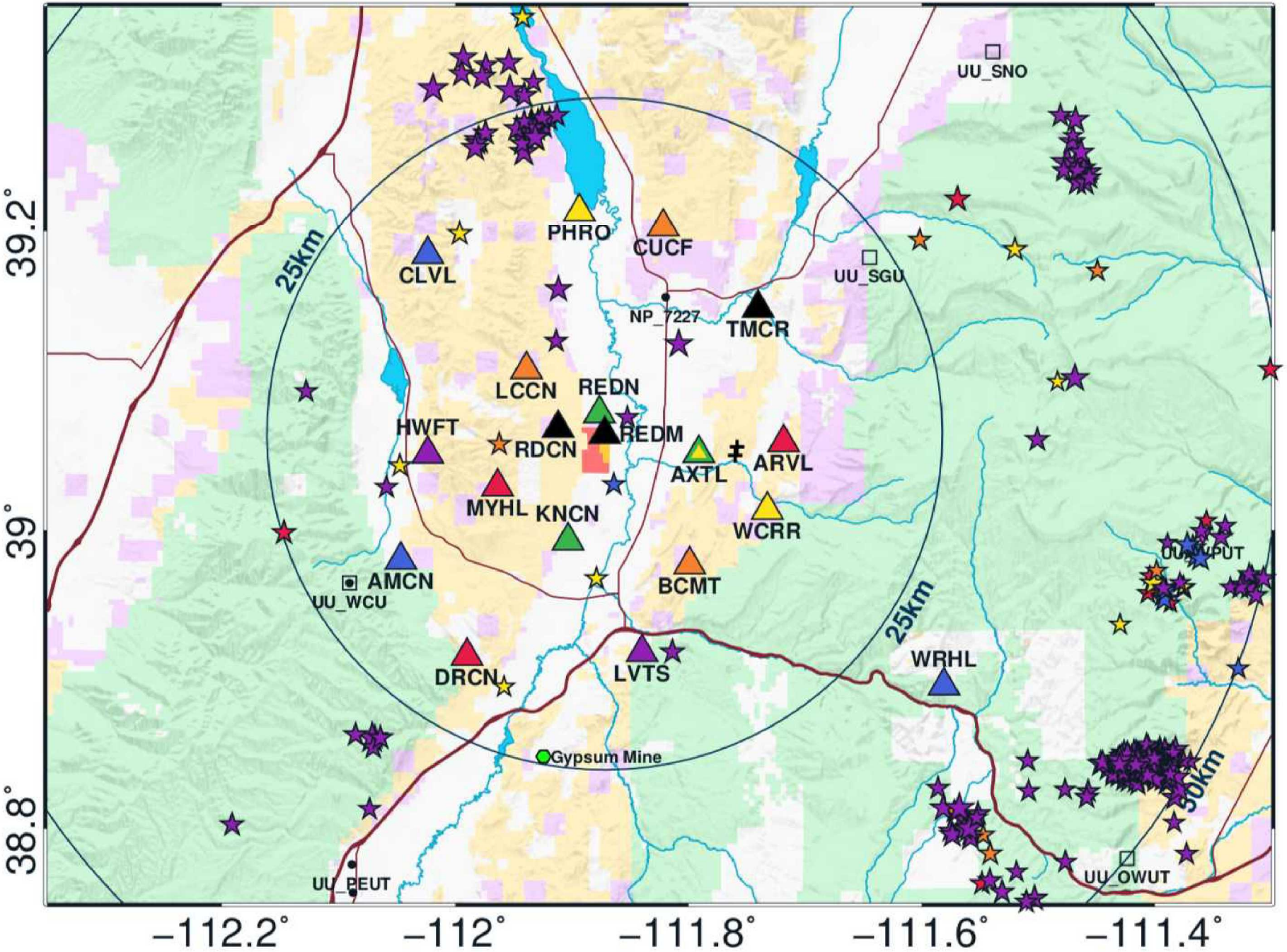
1C	3C	
○	•	FBA
□	■	Short Period
▽	▼	Broad Band
	▲	This Experiment



Basemap

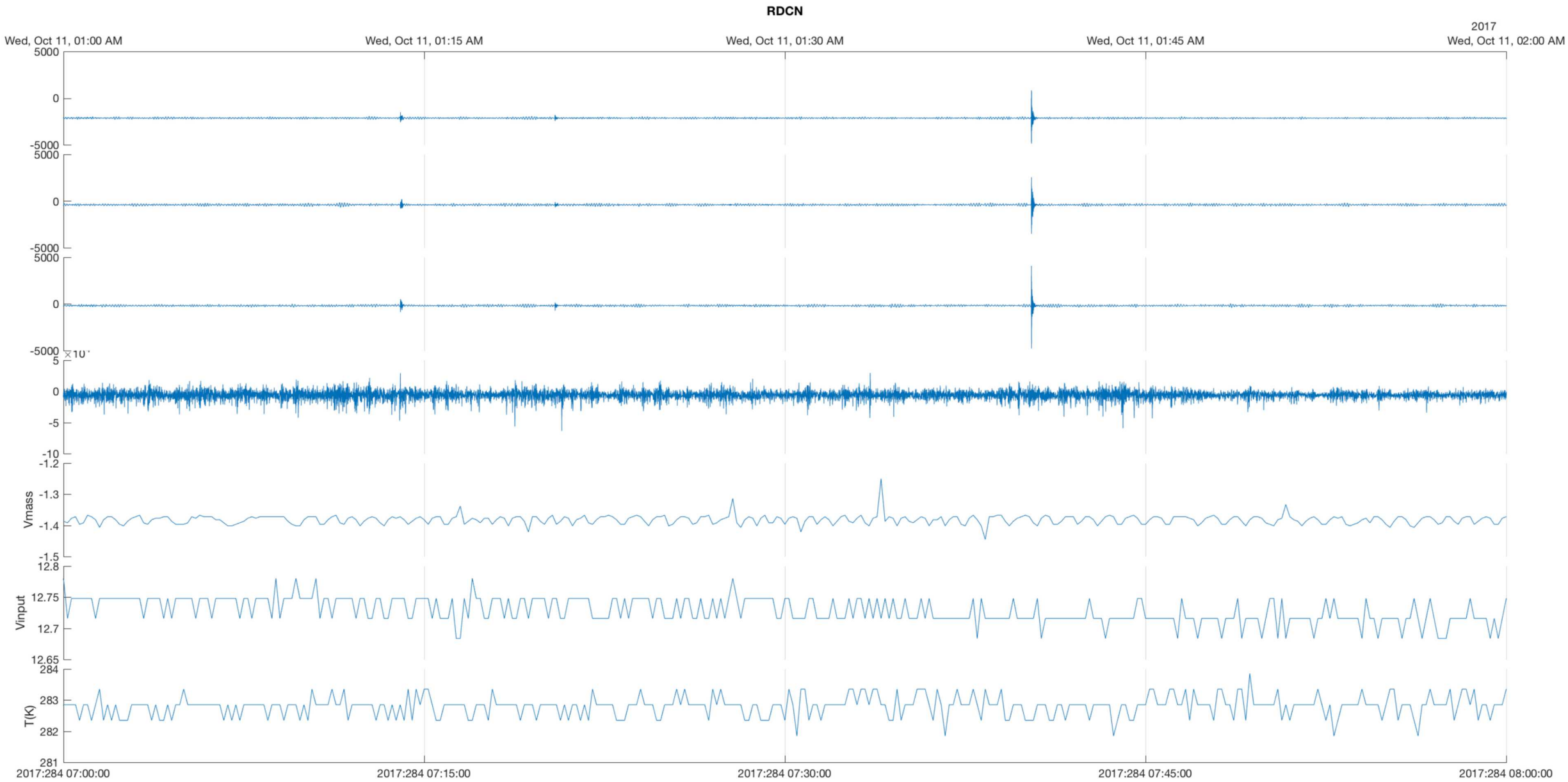
Symbols

- Interstate Highway
- State Highway
- Waterway
- Private
- Redmond Minerals
- Redmond, Inc.
- State of Utah
- BLM
- Forest Service



Station Configuration

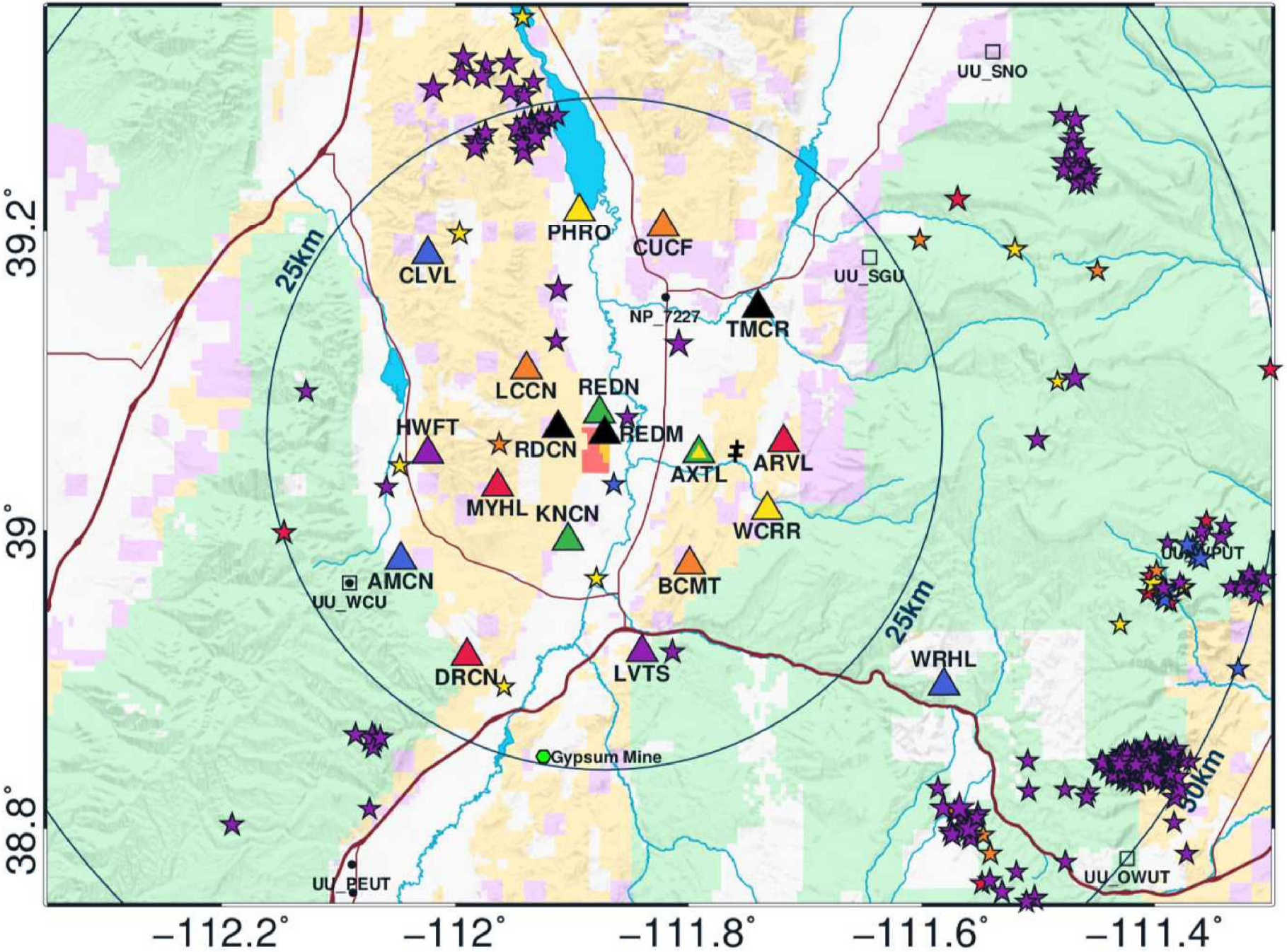
Data Recorded



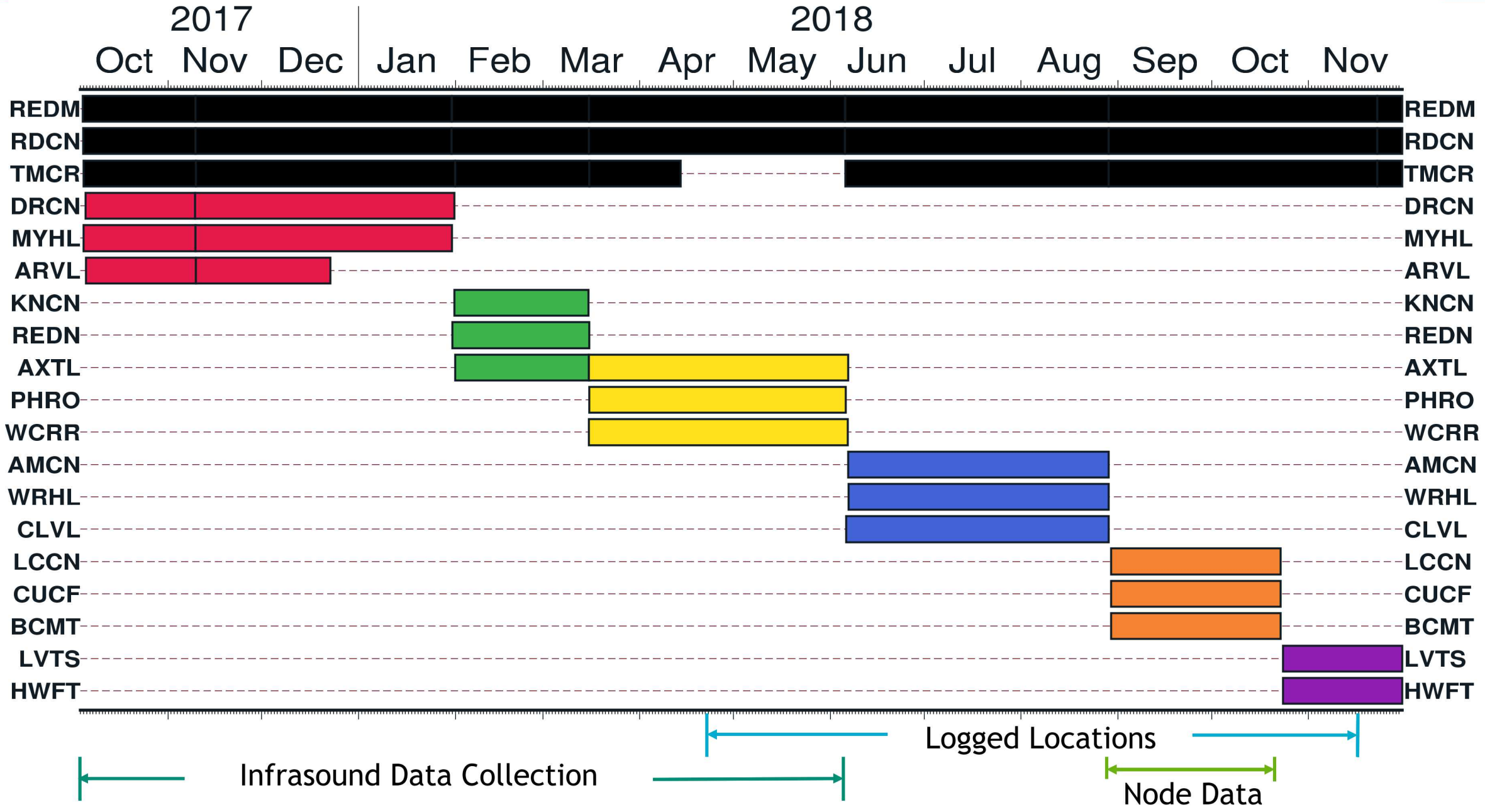
Basemap

Symbols

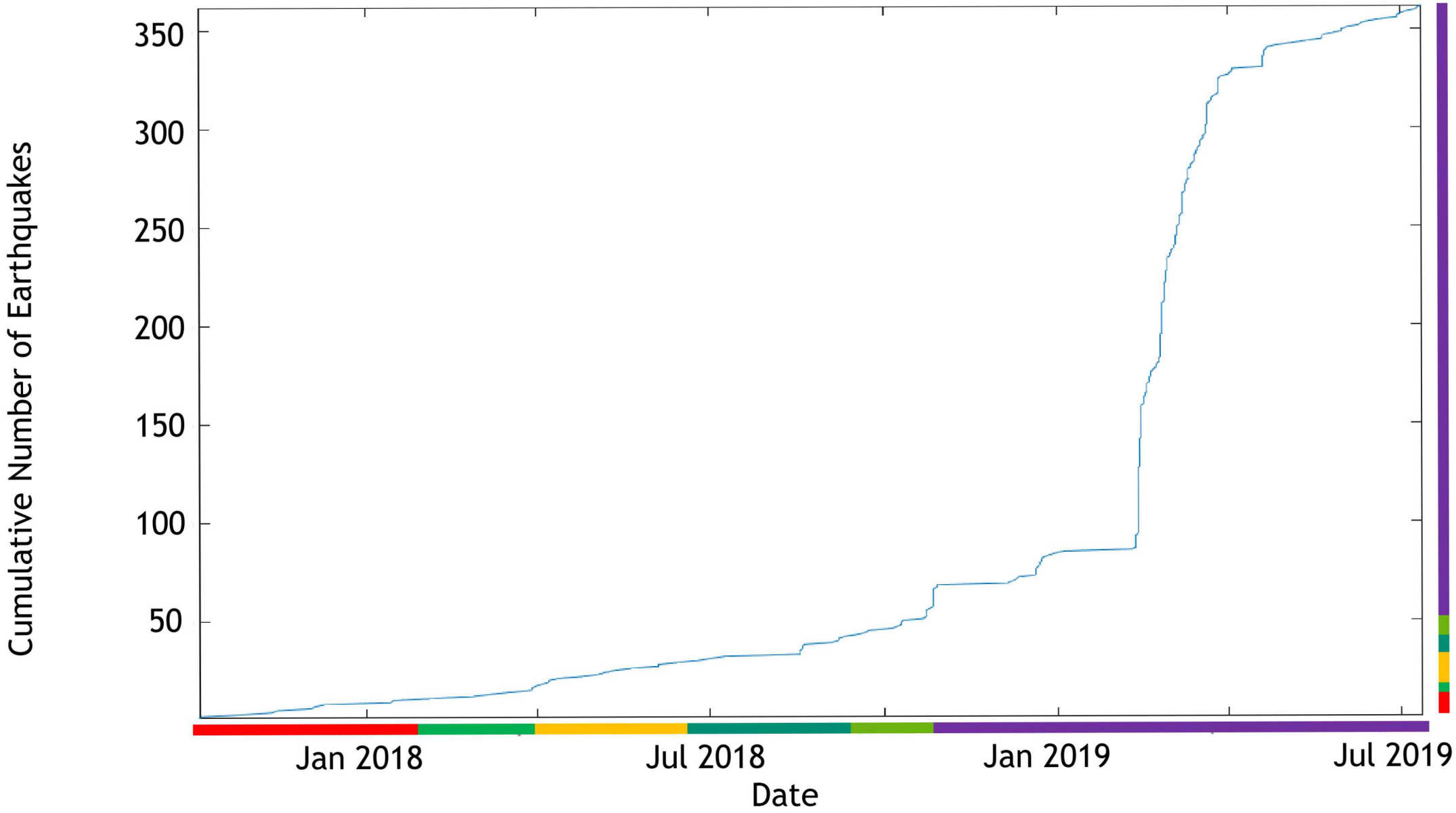
- Interstate Highway
- State Highway
- Waterway
- Private
- Redmond Minerals
- Redmond, Inc.
- State of Utah
- BLM
- Forest Service



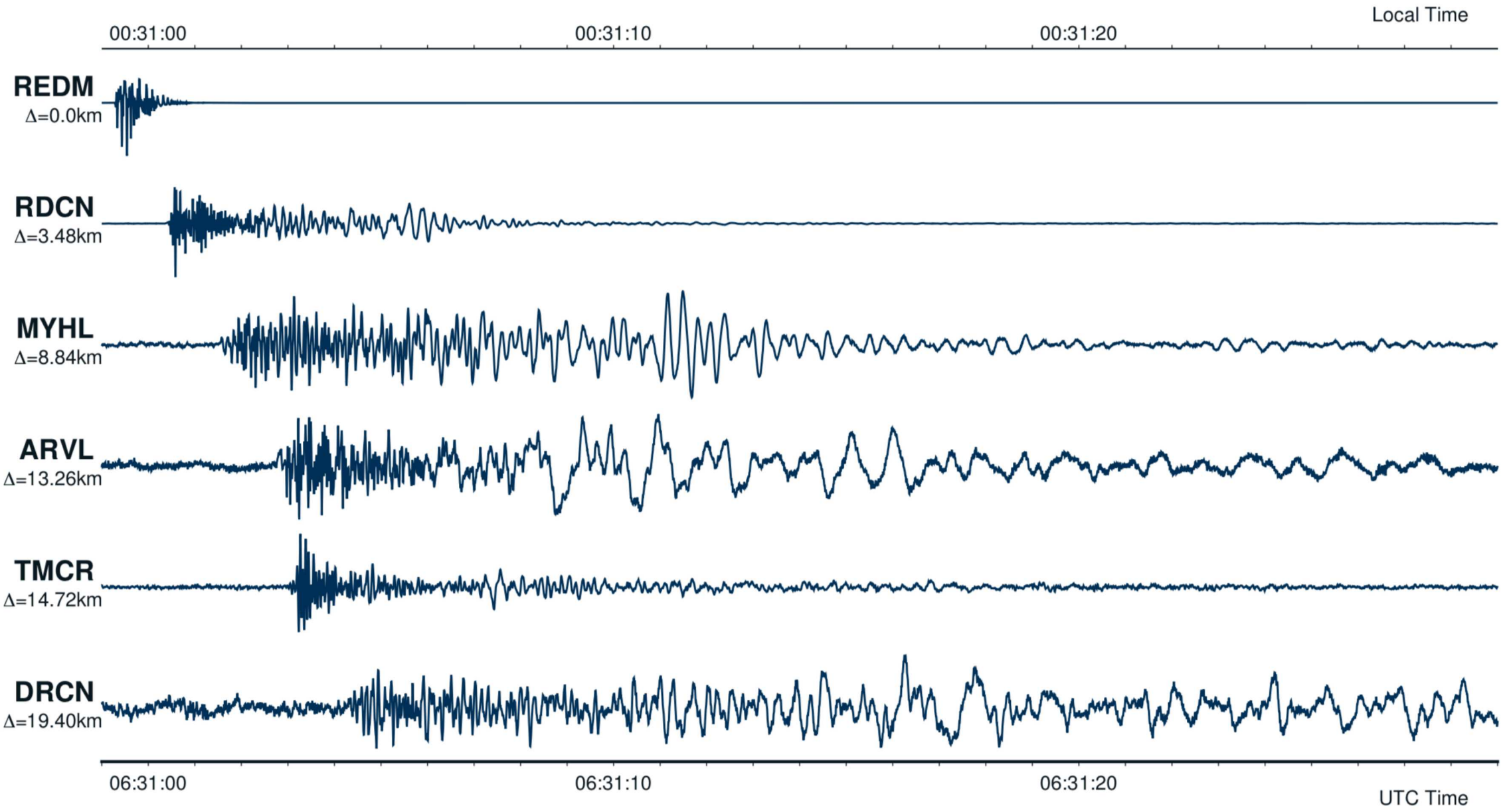
Station Activity



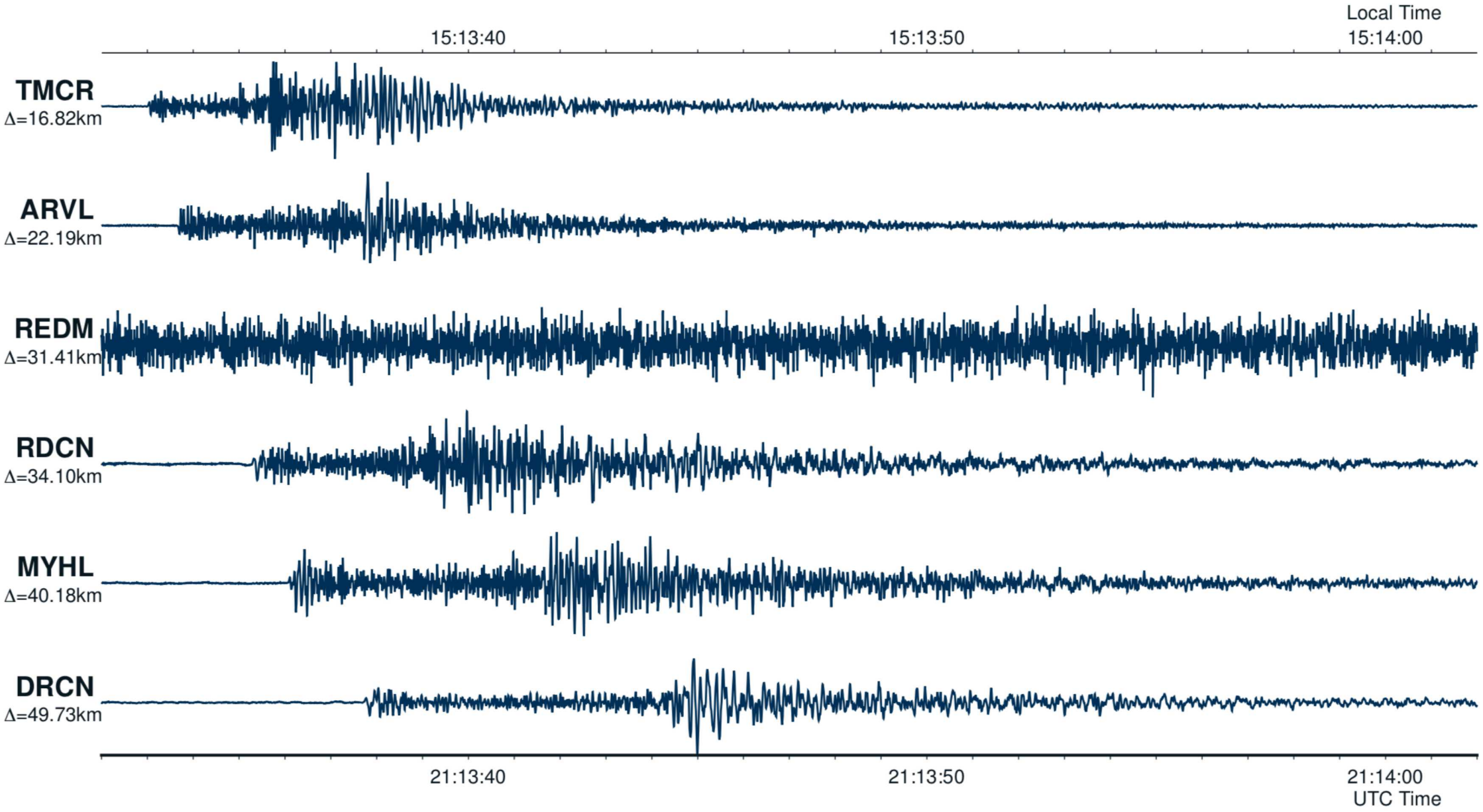
Recorded Earthquakes



Example Recorded Explosion



Example Recorded Earthquake

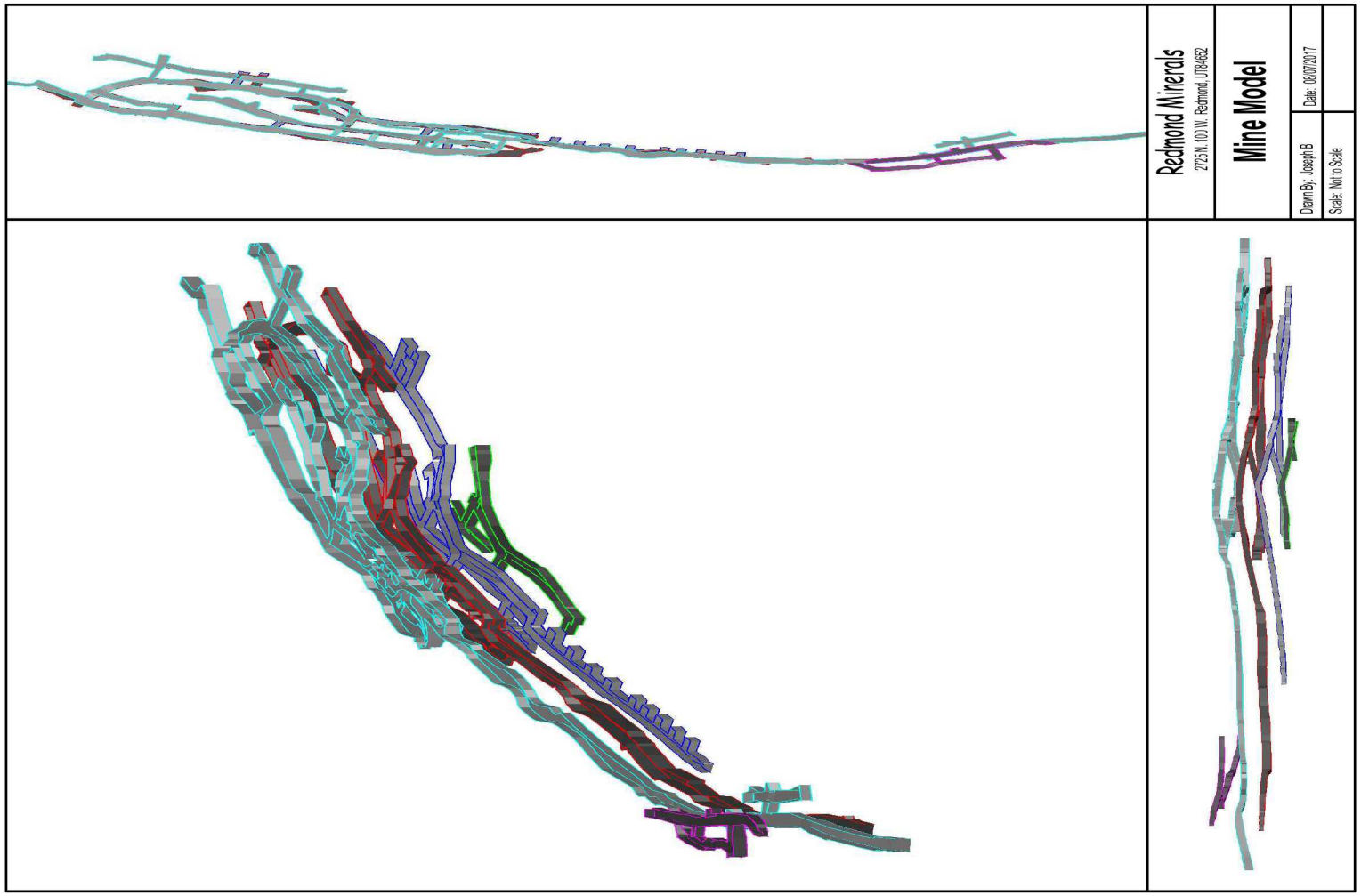


Explosion Source Properties

Explosion Properties

- Several different explosion types:
  - Face, Lifter, Rock, Lead and Asperity
- Face shots most common and are typically 600-800kg TNT equivalent
- Explosives are emplaced in a grid of 14 by 12 holes drilled into the face
- Each explosion lengthens the tunnels by approximately 15 feet
- Detonation pattern consists of 7 separate detonations, radiating out from the center of the face
- Total duration of the detonation pattern is approximately 500ms

Mine Structure



Redmond Salt Mine

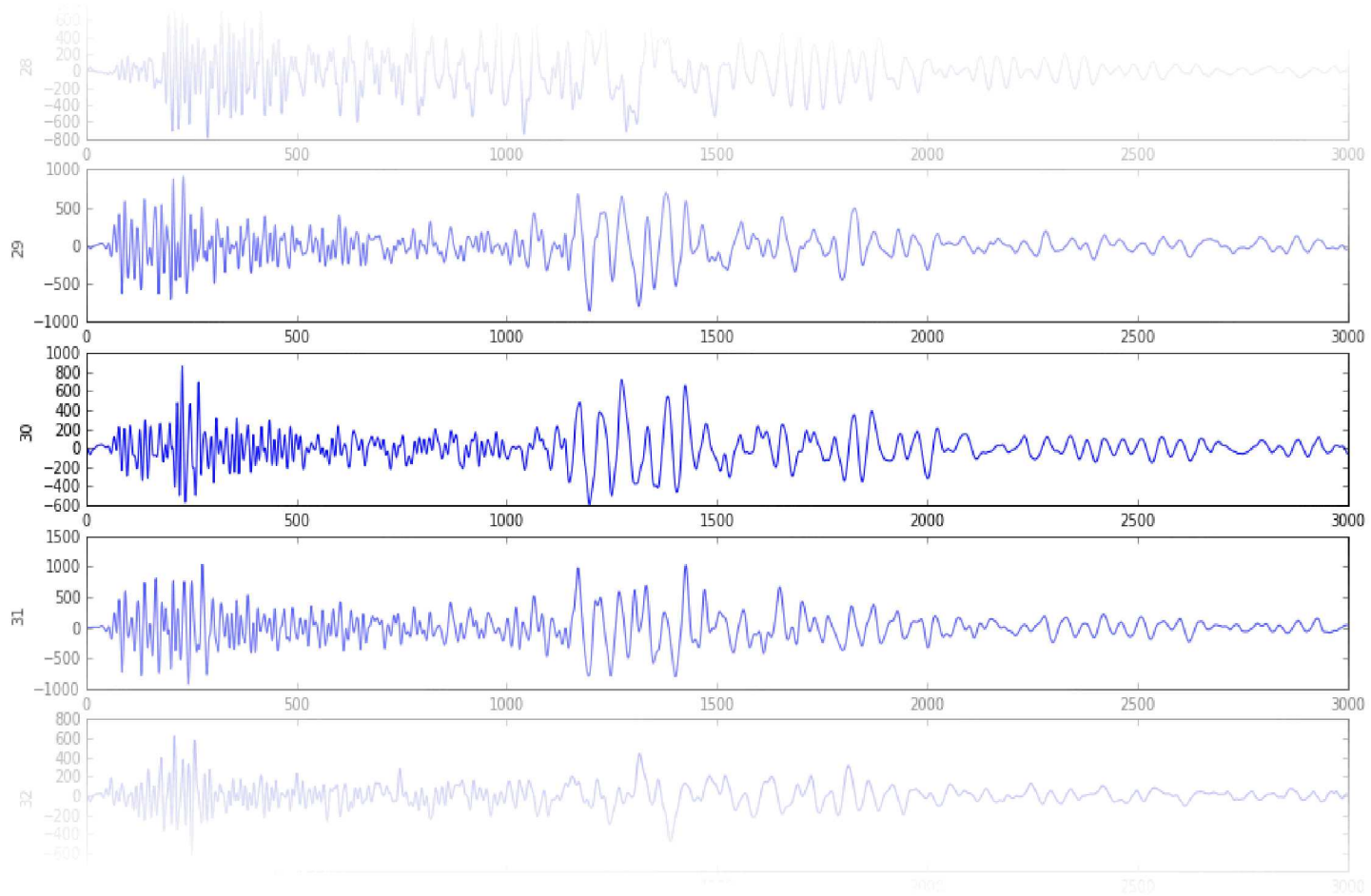
- Over 17 miles of underground tunnels
- Organized into 5 levels
  - AA, A, B, C, D
- Deepest location is ~600 feet below grade
- Rough N-S dimension is 1.5 miles
- Blasting occurs in about a dozen different locations within the mine
- Mined out tunnels are approximately 40 feet by 40 feet

Blasting Log from Mine Operators

Appendix A Catalog of Mine Blasts, Apr 18, 2018 - Nov. 16, 2018

Date & Time	Operator	Mine Level	Drift	Shot Type	Logged Location
2018-04-18 07:36:00	KG	AA	S-Mine	V-Shot	S-Mine-V-Shot
2018-04-18 07:45:00	KG	D	1	Face	1-D
2018-04-18 07:53:00	KG	D	0	Face	0-D
2018-04-19 07:08:00	KG	C	0	Face	0-c
2018-04-19 07:18:00	KG	C	7	Face	7-C-R X-Cuts
2018-04-20 06:51:00	KG	AA	S-Mine	Face	S-Mine
2018-04-20 07:01:00	KG	C	7	Face	7-C R-Main
2018-04-20 07:08:00	KG	D	0	Face	0-D
2018-04-24 07:15:00	DB	D	4	Face	4-D
2018-04-24 07:16:00	DB	D	4	Rock	4-D Rock
2018-04-24 07:26:00	DB	C	7	Face	7C RR xcut
2018-04-25 07:36:00	MC	AA	S-Mine	Face	S-Mine
2018-04-25 07:45:00	MC	C	0	Face	0-C
2018-04-25 07:59:00	MC	D	0	Face	0-D
2018-04-26 07:26:00	DB	AA	S-Mine	Face	S-Mine
2018-04-26 07:35:00	DB	C	0	Face	

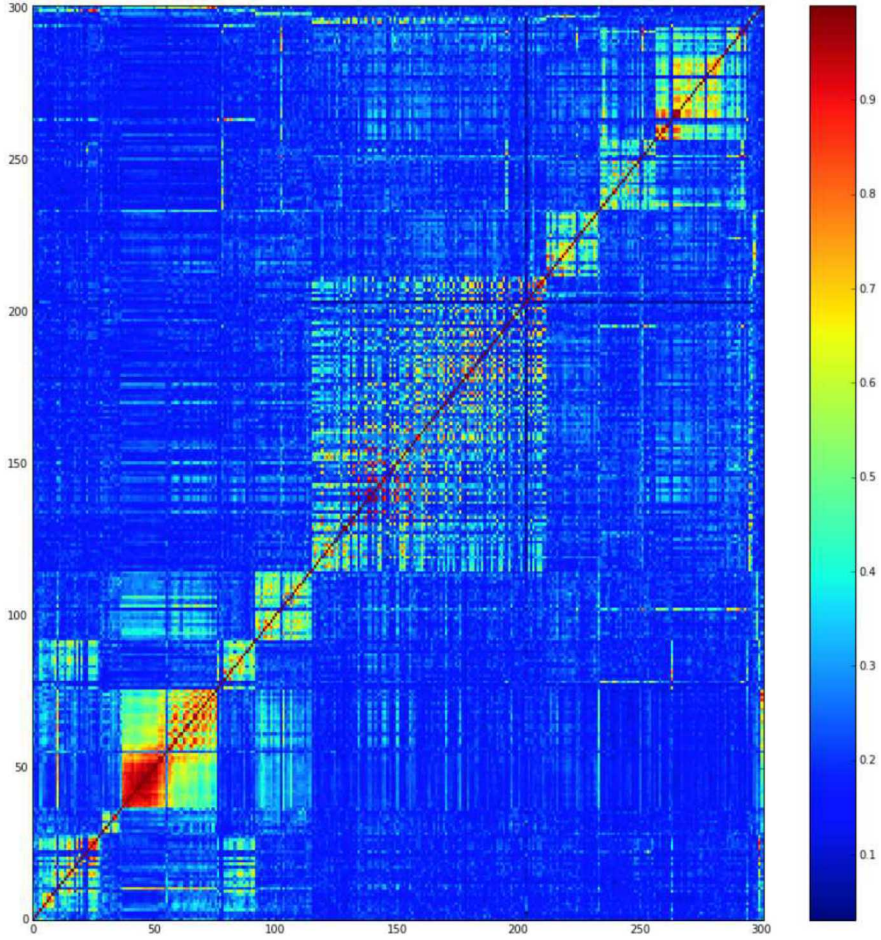
Waveform Correlation of Explosion Signals



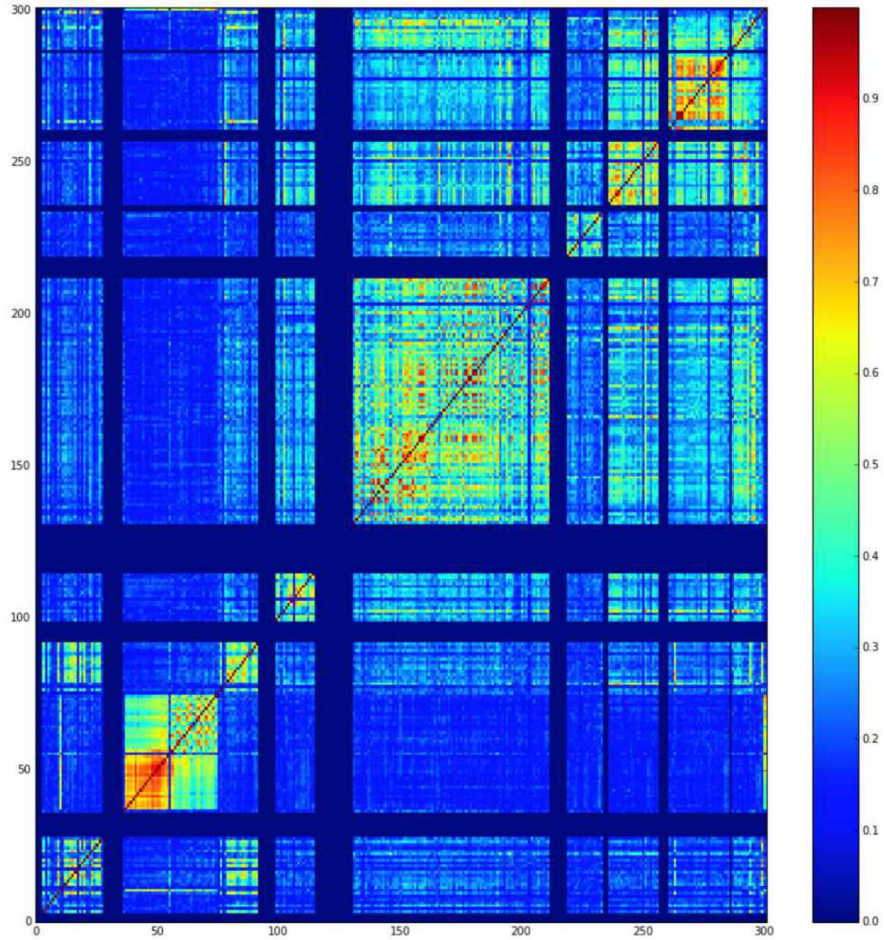
20	260	2018-10-17 07:55:00	JJ	A	0	Face	0A	290	False	NaN	2018-10-17 07:54:13.944
21	266	2018-10-23 07:40:00	DB	A	0	Face	0A	296	False	NaN	2018-10-23 07:40:04.032
22	268	2018-10-24 07:10:00	DB	A	0	Face	1D XCut	297	False	NaN	2018-10-24 07:09:00.656
23	273	2018-10-25 07:15:00	MC	A	0	Face	0A main	298	False	NaN	2018-10-25 07:13:36.300
24	284	2018-10-31 22:02:00	MP	A	0	Face	0-A	304	False	NaN	2018-10-31 22:00:50.356
25	287	2018-11-06 08:36:00	DB	A	0	Face	0A	310	False	NaN	2018-11-06 08:35:08.428
26	302	2018-11-14 08:56:00	MR	A	0	Face	0A	318	False	NaN	2018-11-14 08:56:26.664
27	307	2018-11-16 08:26:00	MR	A	0	Face	0A	320	False	NaN	2018-11-16 08:26:28.836
28	18	2018-04-27 07:37:00	MC	A	8	Face	8A	117	False	NaN	2018-04-27 07:38:53.596
29	0	2018-04-18 07:36:00	KG	AA	S-Mine	V-Shot	S-Mine-V-Shot	108	False	NaN	2018-04-18 07:36:06.228
30	5	2018-04-20 06:51:00	KG	AA	S-Mine	Face	S-Mine	109	False	Logged day was one day too early.	2018-04-20 06:51:07.288
31	11	2018-04-25 07:36:00	MC	AA	S-Mine	Face	S-Mine	115	False	NaN	2018-04-25 07:35:31.704
32	14	2018-04-26 07:26:00	DB	AA	S-Mine	Face	S-Mine	116	False	NaN	2018-04-26 07:25:56.552
33	24	2018-05-03 07:08:00	KG	AA	S-Mine	Face	South Mine	123	False	NaN	2018-05-03 07:08:48.608
34	36	2018-05-24 08:04:00	DB	AA	S-Mine	Face	S mine	144	False	NaN	2018-05-24 08:04:47.308
35	40	2018-05-25 06:47:00	MC	AA	S-Mine	Face	S-mine	145	False	NaN	2018-05-25 06:48:59.700
36	58	2018-06-07 07:23:00	DB	AA	S-Mine	NaN	sm corners	158	False	Double Event.	2018-06-07 07:23:01.460
37	63	2018-06-13 06:57:00	KG	AA	S-Mine	Face	S-Mine	164	False	NaN	2018-06-13 06:57:25.916
38	68	2018-06-14 06:59:00	KG	AA	S-Mine	Face	South Mine	165	False	NaN	2018-06-14 06:59:...

Matrix of Correlation Values

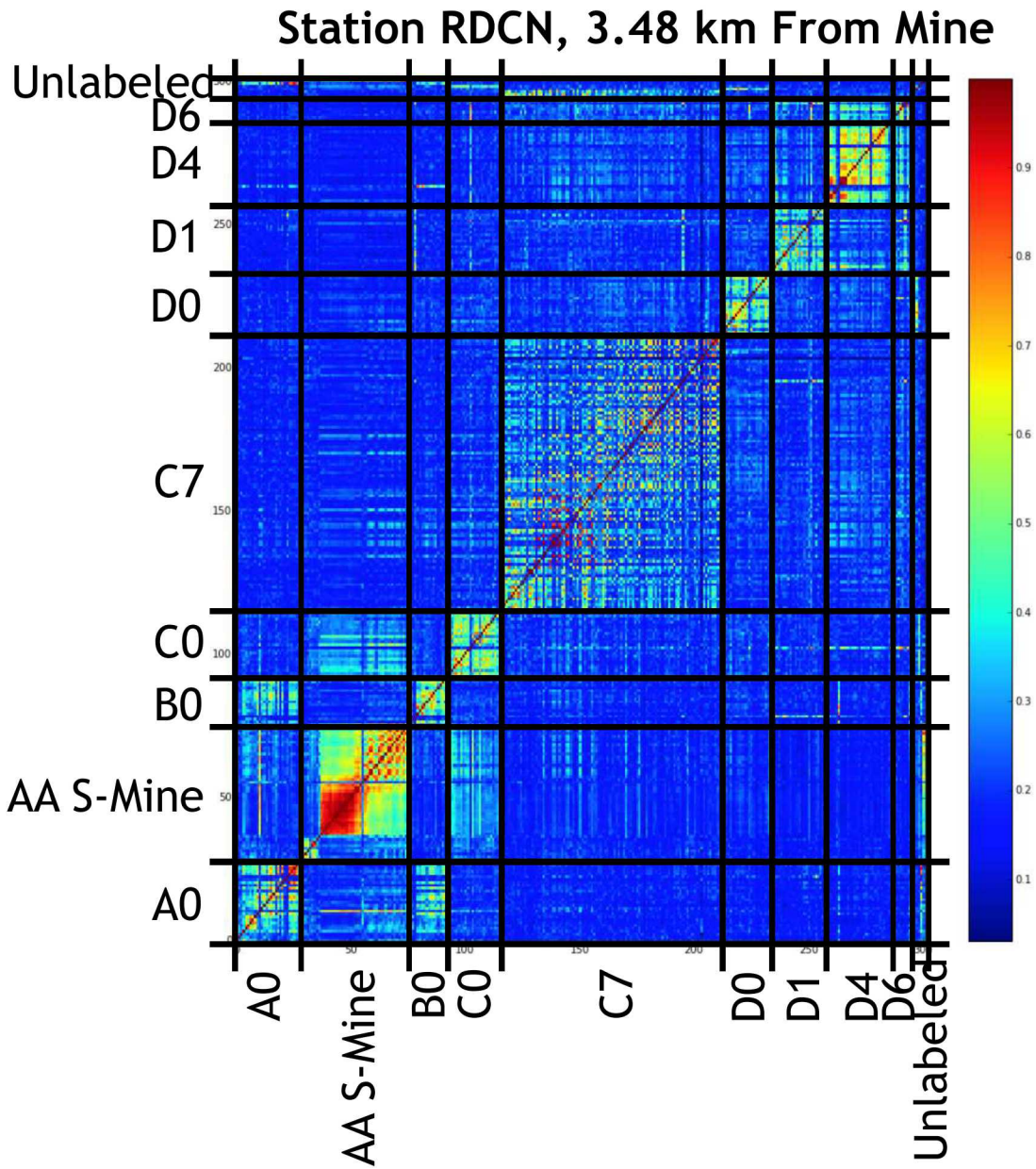
Station RDCN, 3.48 km From Mine

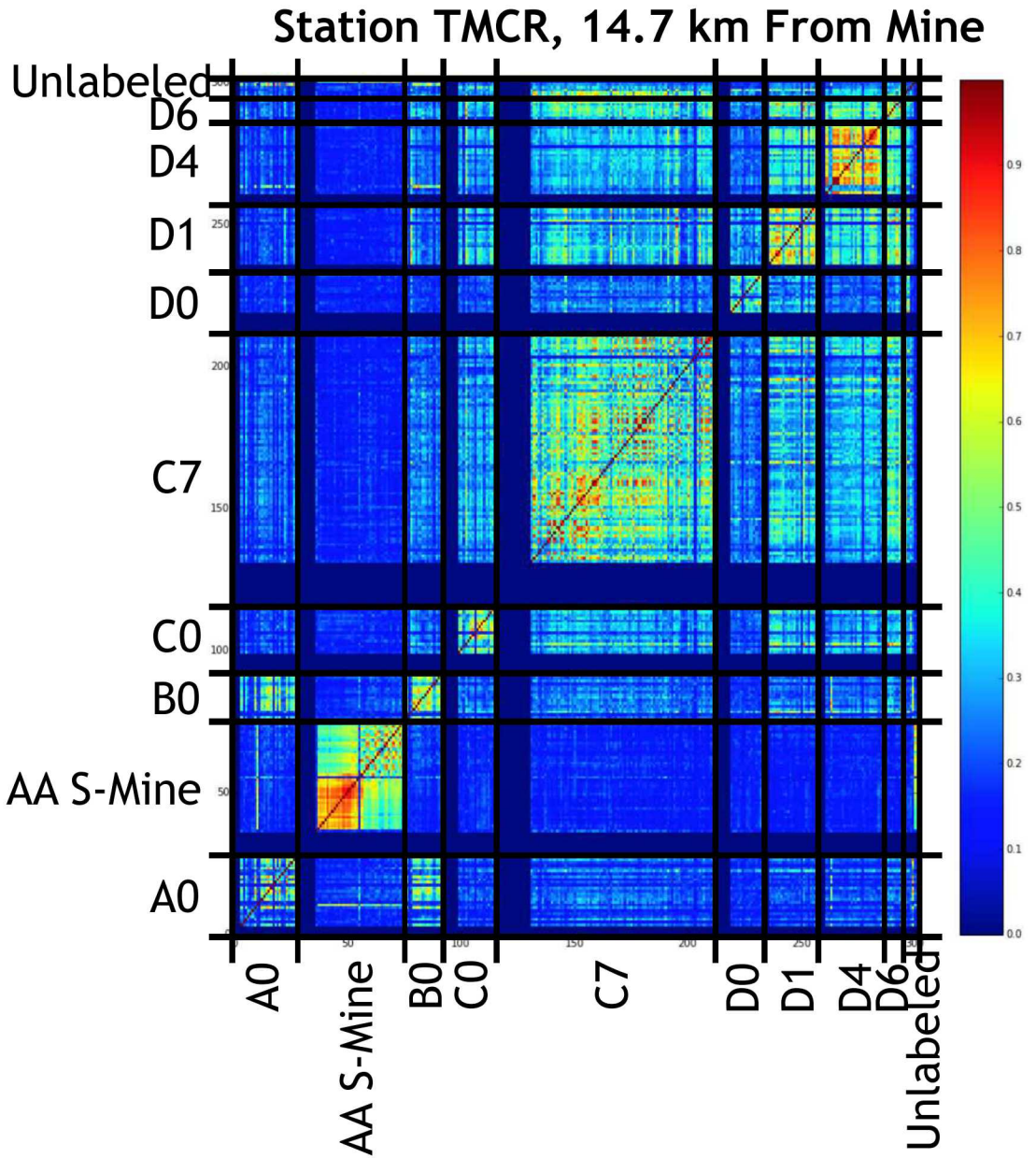


Station TMCR, 14.7 km From Mine

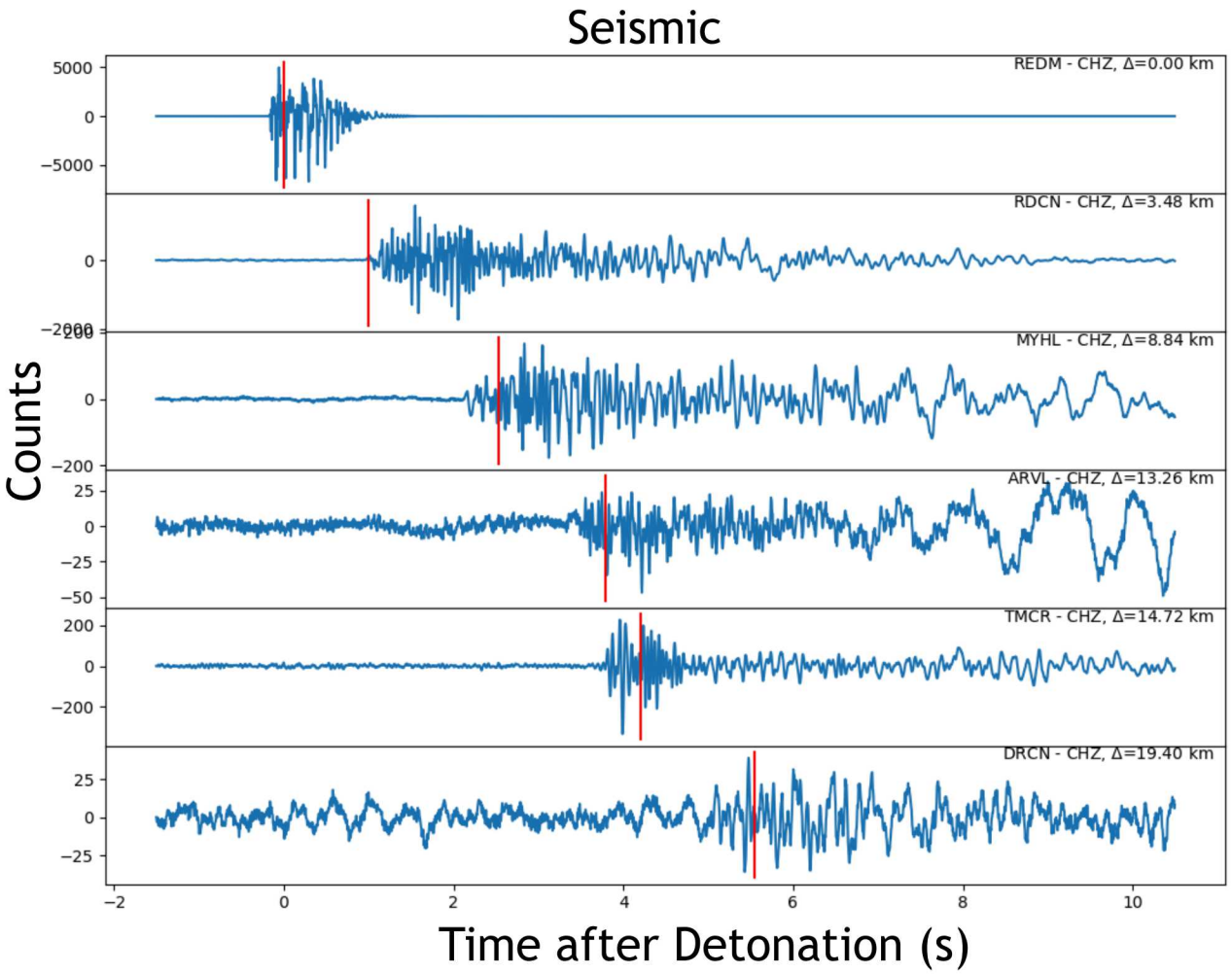


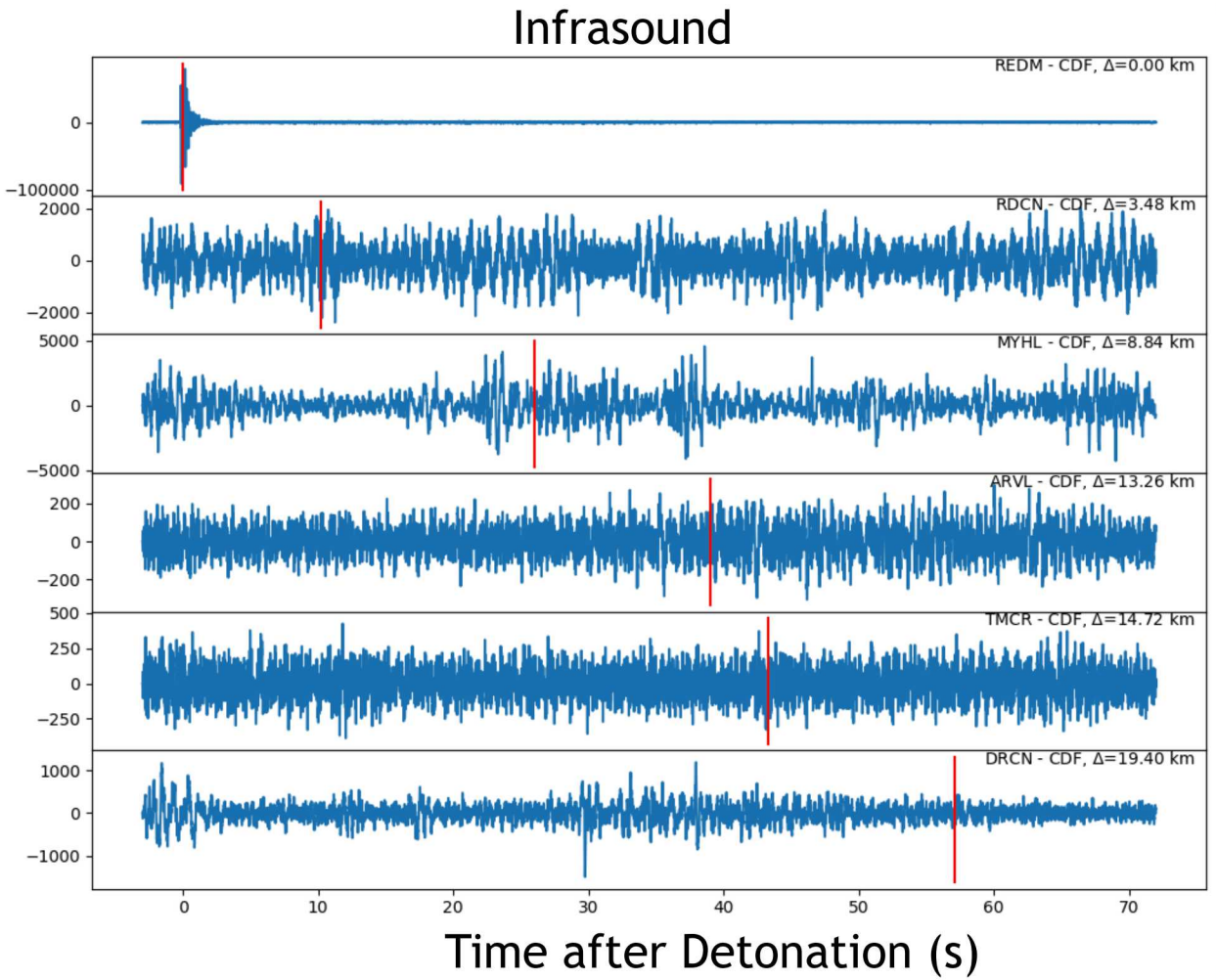
Matrix of Correlation Values



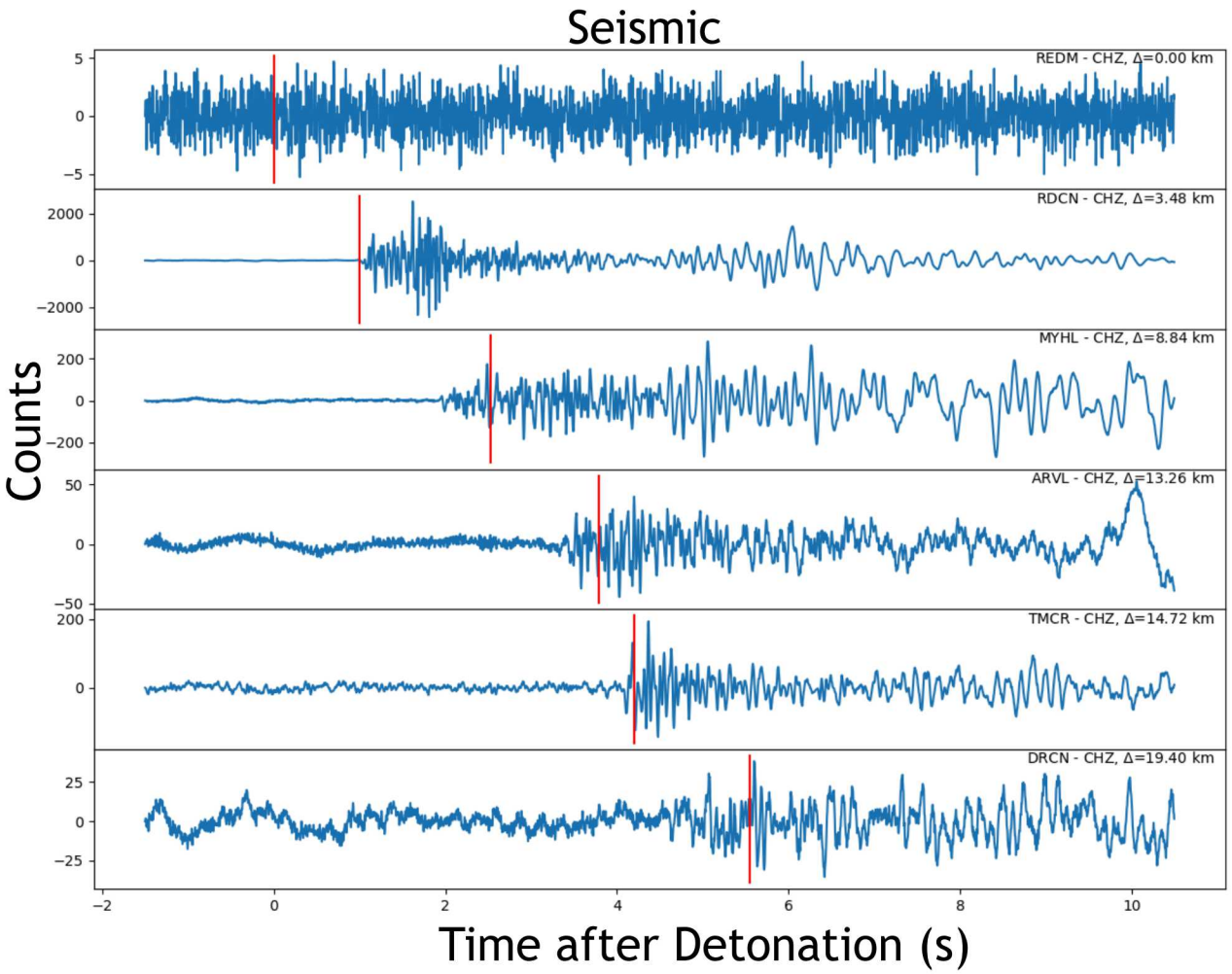


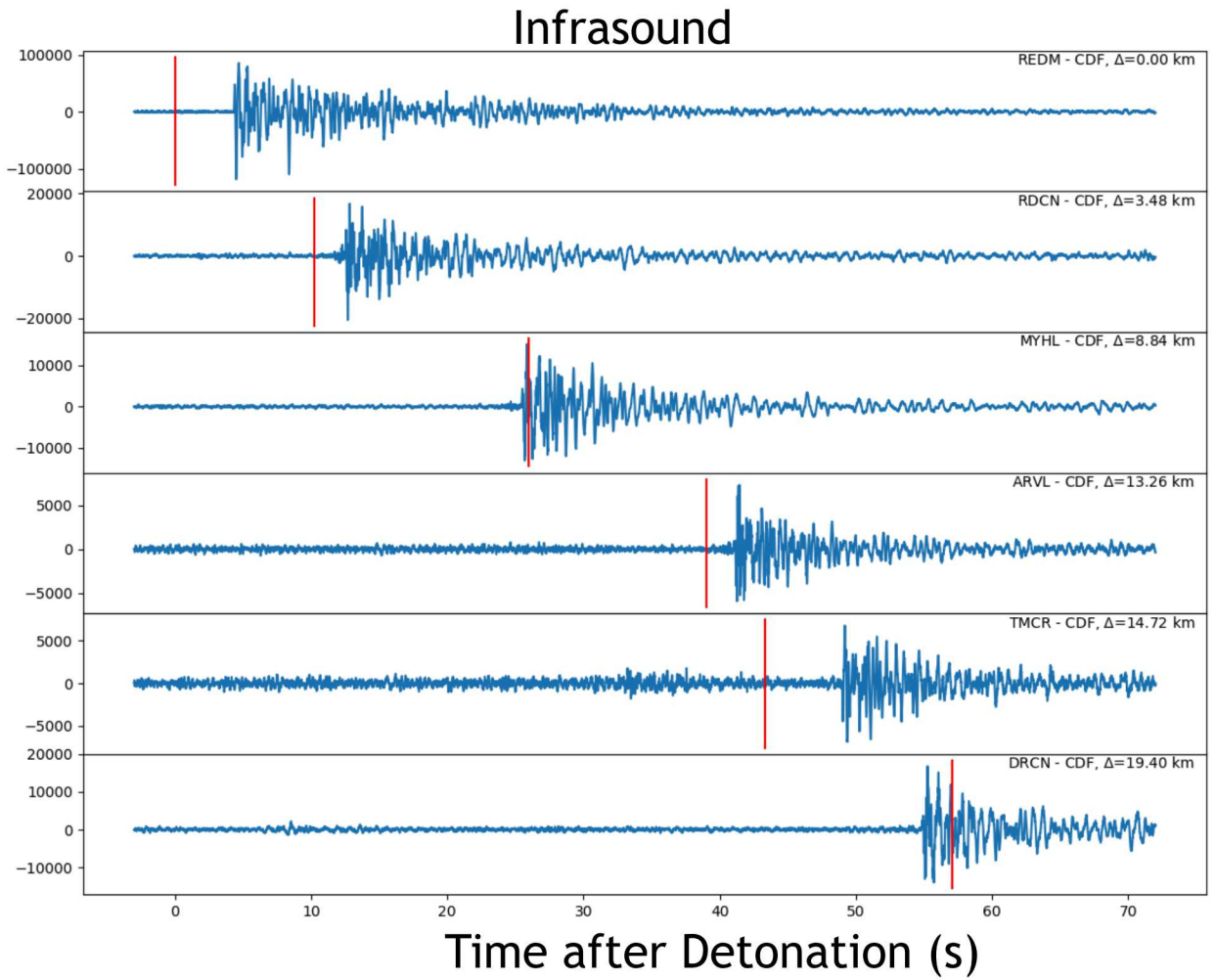
Tunnel Infrasound Signals





Tunnel Infrasound Signals





Tunnel Infrasound Signals

Why do some events generate strong infrasound arrivals?

- Atmospheric conditions?
- Position in mine?
  - Does mine structure contain signals from lower levels?

The data in these tables are consistent with the idea that position in the mine is most import factor, however a waveform correlation and clustering analysis is needed to confirm.

Infrasound data collection: 10/5/17-6/5/18 (243 Days)

		Rate (blasts/day)
Number of Events with Strong infrasound arrivals	49 (15%)	0.20
Number of events with any infrasound arrivals	106 (32%)	0.43
Total Number of Explosions	333	1.4

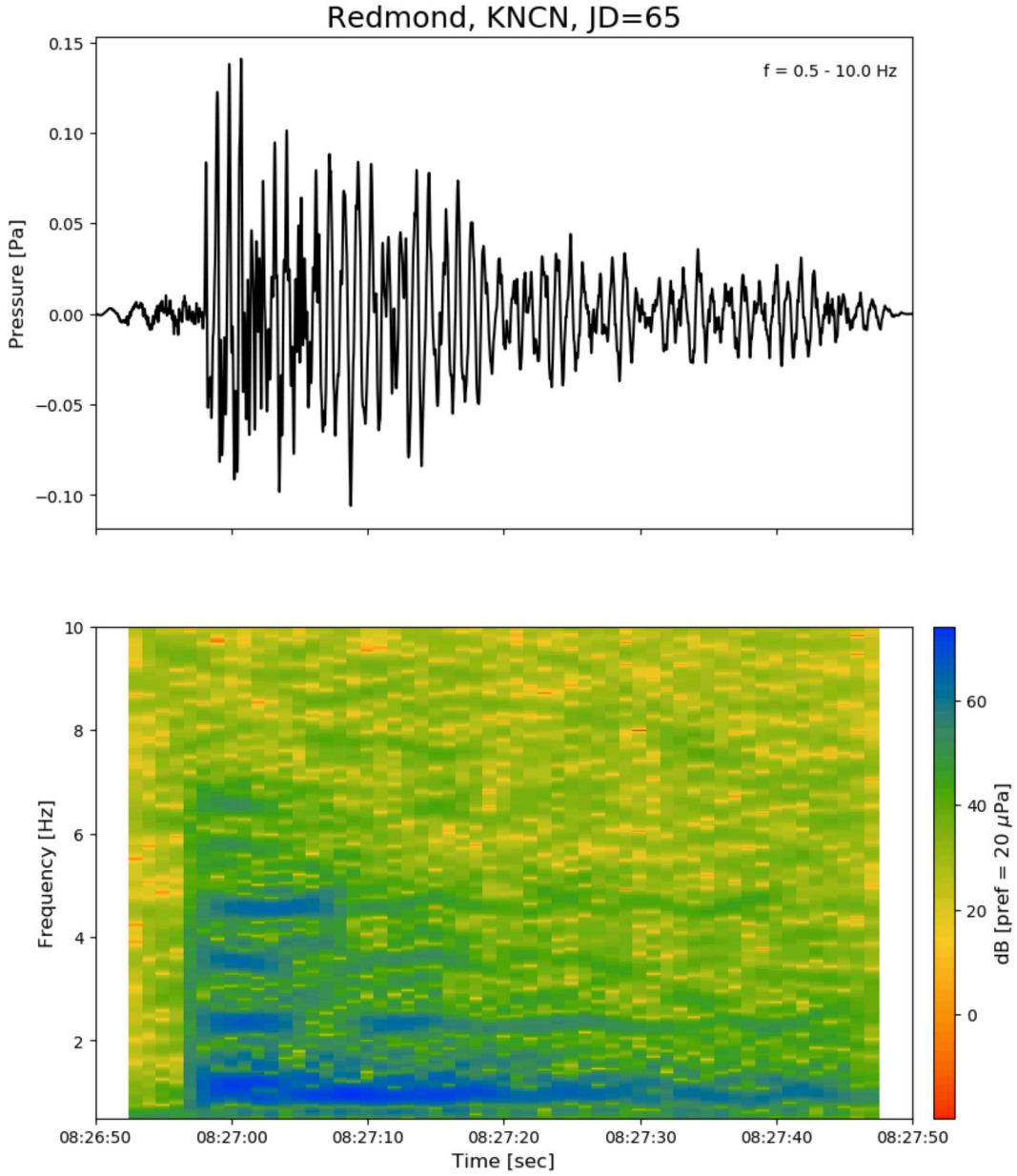
Log Date Range: 4/18/18-11/16/18 (212 Days)

Mine Level	Number of Explosions	Rate (blasts/day)
AA	47 (15%)	0.22
A	32 (10%)	0.15
B	16 (5%)	0.075
C	123 (40%)	0.58
D	83 (27%)	0.39
No Level Specified	7 (2%)	0.033
All Levels	308	1.5

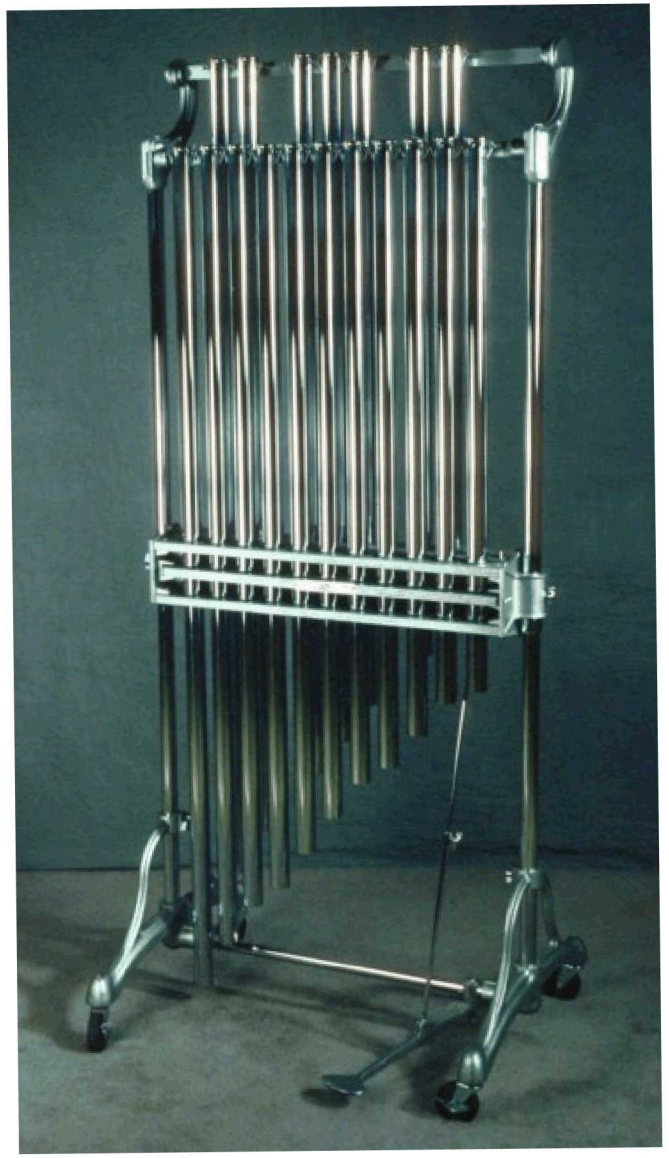
Tunnel Infrasound Signals

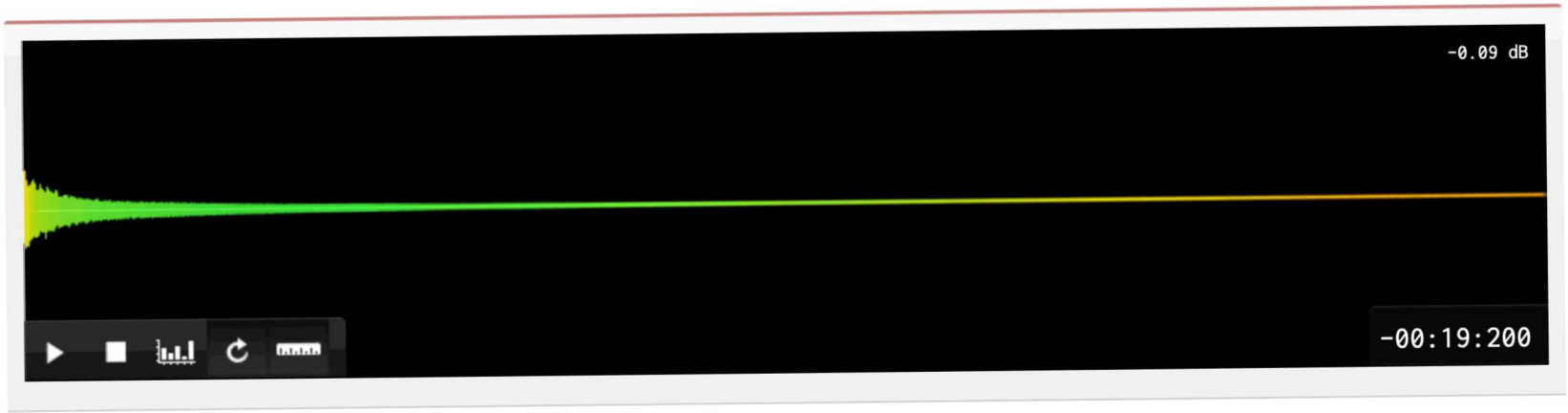
The recorded signals contain an interesting harmonic structure

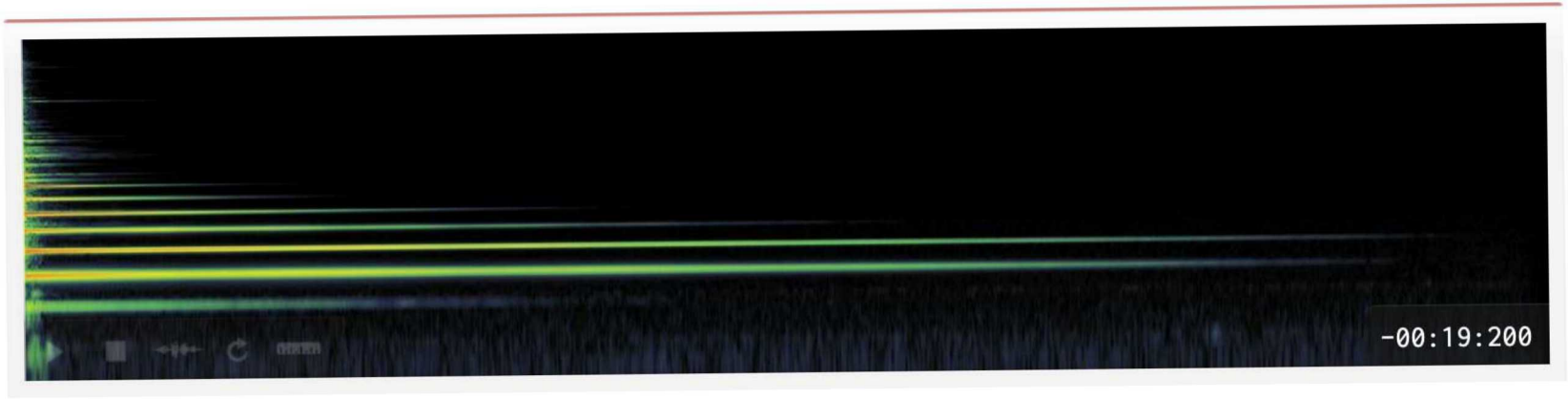
- Is this structure consistent with a model of a vibrating air column in a long tube?
- Can we infer characteristics of mine structure from these signals?
- If so, do these signals change as tunnel geometry changes?



Tunnel Infrasound Signals – Tubular Bells Analogue





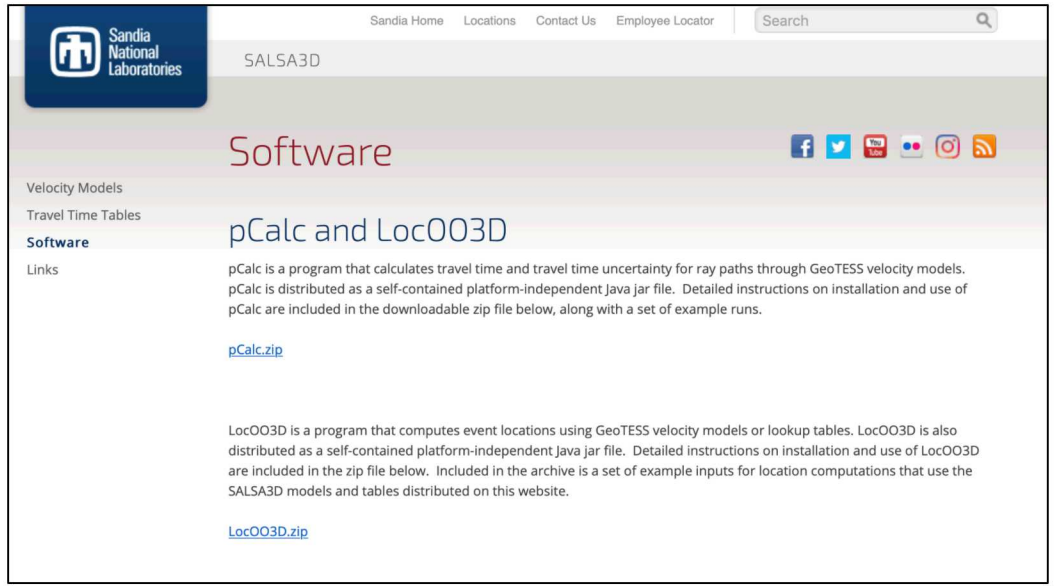


Seismic Event Locations – Ground Truth

Appendix A Catalog of Mine Blasts, Apr 18, 2018 - Nov. 16, 2018

Date & Time	Operator	Mine Level	Drift	Shot Type	Logged Location
2018-04-18 07:36:00	KG	AA	S-Mine	V-Shot	S-Mine-V-Shot
2018-04-18 07:45:00	KG	D	1	Face	1-D
2018-04-18 07:53:00	KG	D	0	Face	0-D
2018-04-19 07:08:00	KG	C	0	Face	0-c
2018-04-19 07:18:00	KG	C	7	Face	7-C-R X-Cuts
2018-04-20 06:51:00	KG	AA	S-Mine	Face	S-Mine
2018-04-20 07:01:00	KG	C	7	Face	7-C R-Main
2018-04-20 07:08:00	KG	D	0	Face	0-D
2018-04-24 07:15:00	DB	D	4	Face	4-D
2018-04-24 07:16:00	DB	D	4	Rock	4-D Rock
2018-04-24 07:26:00	DB	C	7	Face	7C RR xcut
2018-04-25 07:36:00	MC	AA	S-Mine	Face	S-Mine
2018-04-25 07:45:00	MC	C	0	Face	0-C
2018-04-25 07:59:00	MC	D	0	Face	0-D
2018-04-26 07:26:00	DB	AA	S-Mine	Face	S-Mine
2018-04-26 07:35:00	DB	C	0	Face	

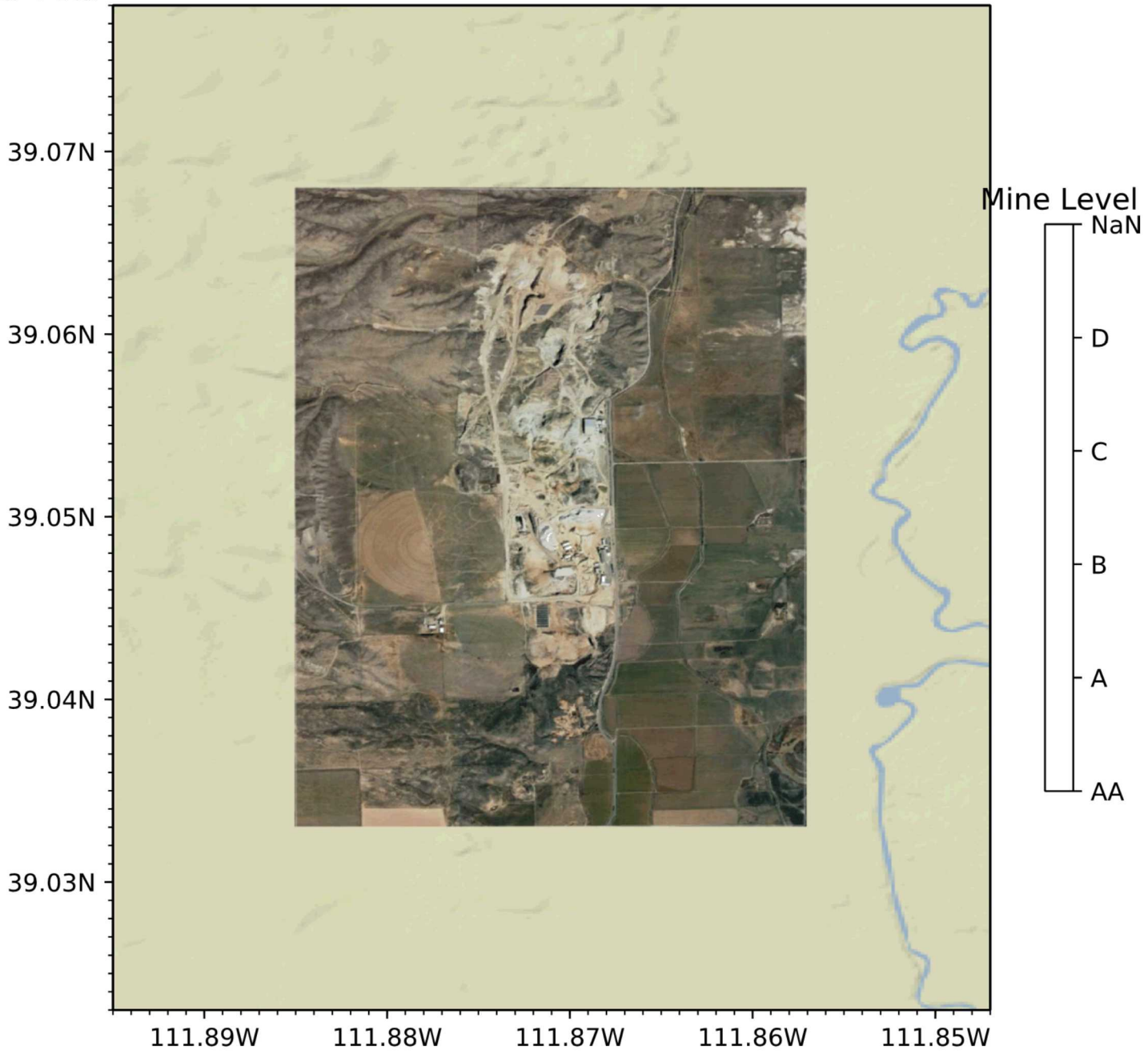
Locating Mine Explosions



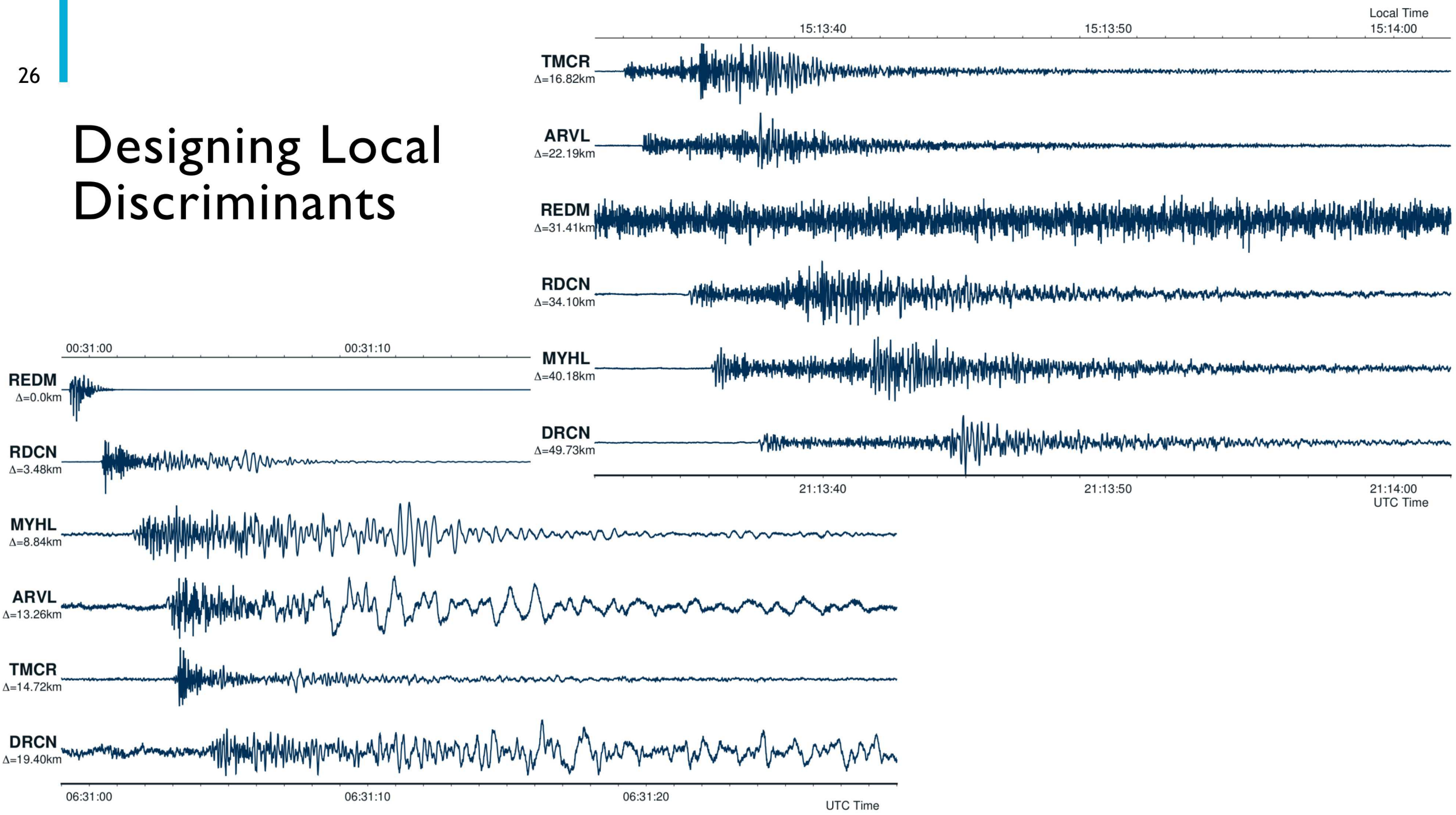
www.sandia.gov/salsa3d/Software.html

Elizabeth Berg – Summer Intern

- Located events using broadband and nodal stations
- Event locations were precise even with poor velocity model when all data were used



Designing Local Discriminants



Conclusions/Future Work

We have obtained a rich dataset of local seismic and infrasound events

- Recorded approximately 1000 mining explosions
- Ground-truth locations for 300 of these
  - AutoCAD model of the mine
  - Blasting logs from mine operators
- Recorded several hundred local earthquakes

Ongoing analysis

- Location algorithm testing using ground-truth events
- Investigations of properties of infrasound signals

Future work

(1) Investigations into velocity inversion of the region surrounding the mine
(2) Testing local discrimination methods using the explosion and earthquake signals
(3) **Data Release** strategy

Onboard Processing System

Onboard Processing System

Problem

Small-event monitoring requires close proximity to monitoring regions. Often these regions are access limited both physically and telemetrically.

Approach

Develop autonomous sensing platforms that can apply data processing workflows in the field and then communicate summary information back to analysts.

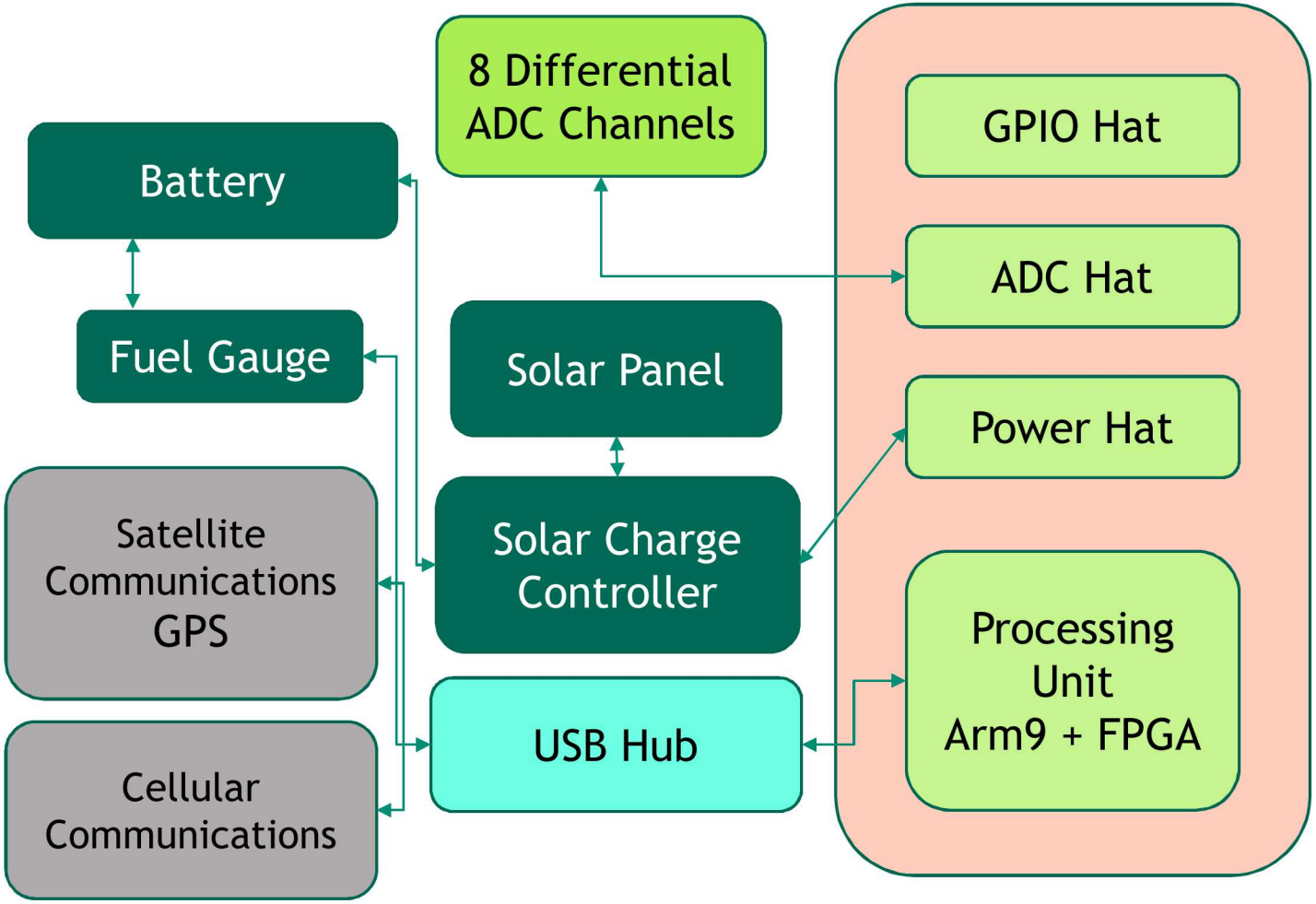
Goals

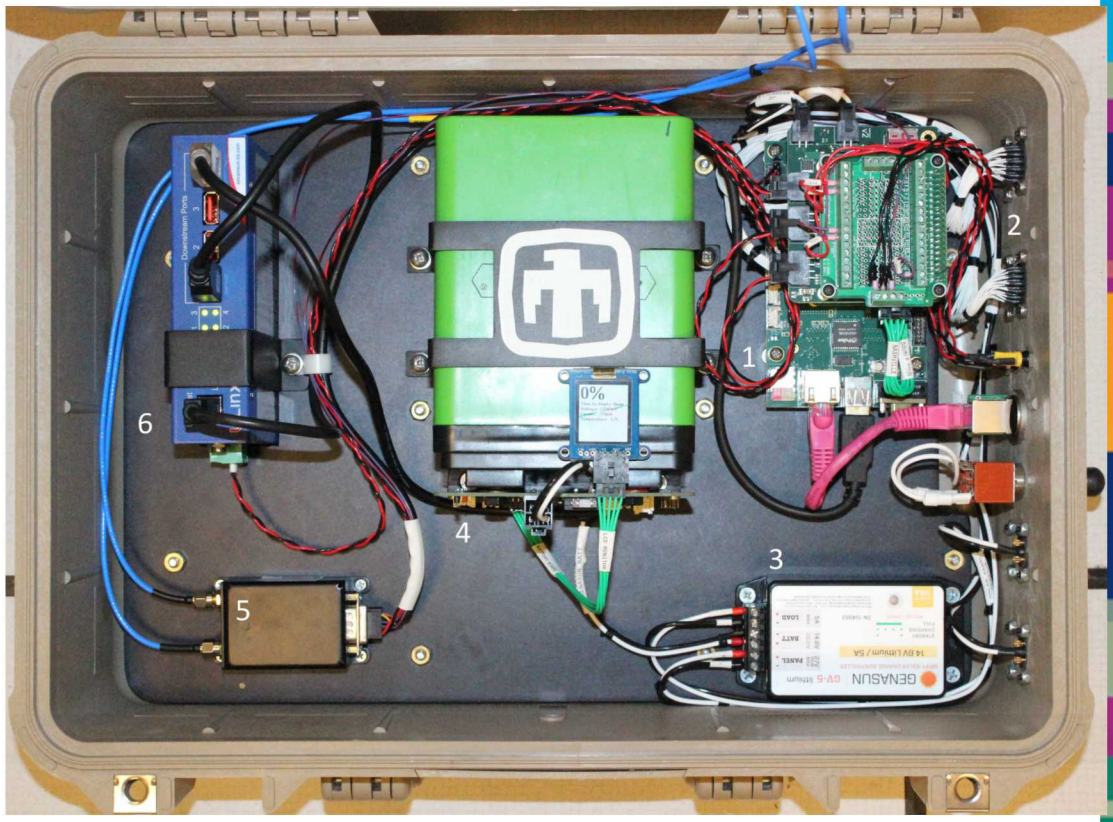
(1) Develop a prototype sensing platform which has onboard computing/processing capability
(2) Test the performance of this platform in a variety of weather conditions and over a long period of time
(3) Design efficient algorithms capable of sophisticated onboard processing within computational constraints

Onboard Processing Platform

Design Specifications	Realized Platform
Digitize at least four channels at sample rates up to 1kHz at 24 bit resolution, GPS disciplined	Records on up to eight channels at sample rates up to 2kHz at 24 bit resolution, GPS disciplined
Capable of indefinite remote operation with power to sensors	Solar charged Li-ion batteries with optional external battery packs, capable of powering instruments
Data logging capability for raw data retrieval	Data is logged to internal SD card for easy retrieval
Onboard processing capability allowing sophisticated processing workflows	Onboard processing capability provided by ARM9 processor and associated FPGA
Exfiltration of analysis products via satellite or cellular communication	Remote interaction and data download available using both satellite and cellular pathways
Inter-node communication capability	Inter-node communication via external cellular or satellite communications

Platform Design



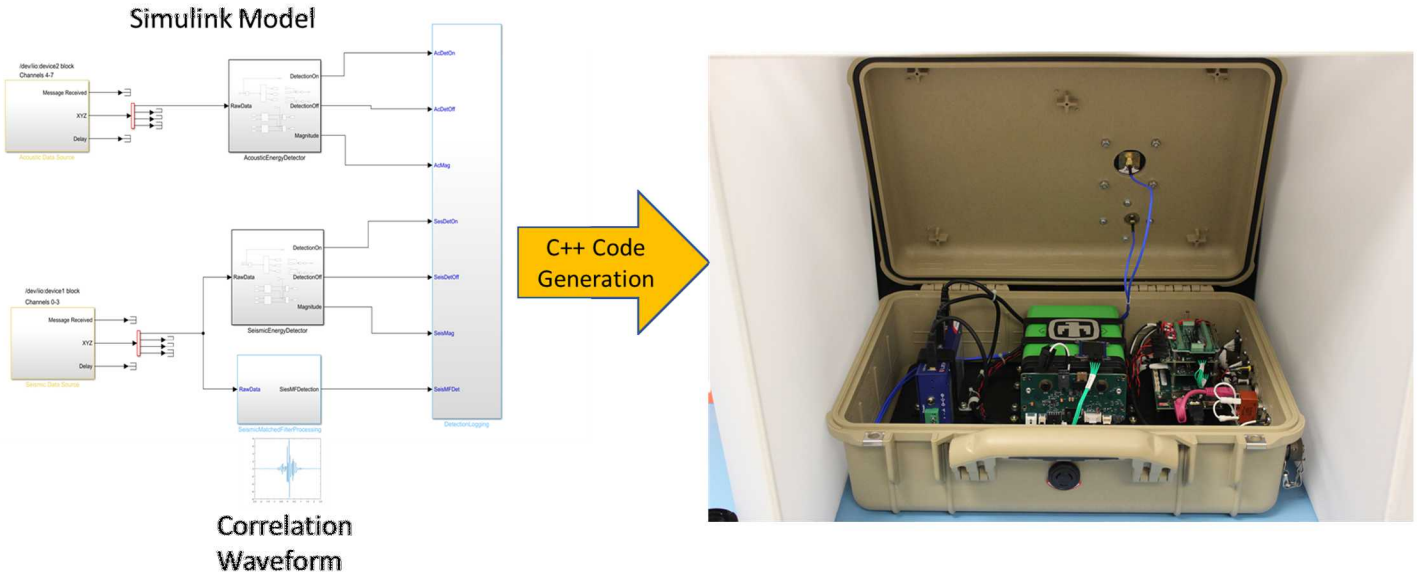


Field Testing

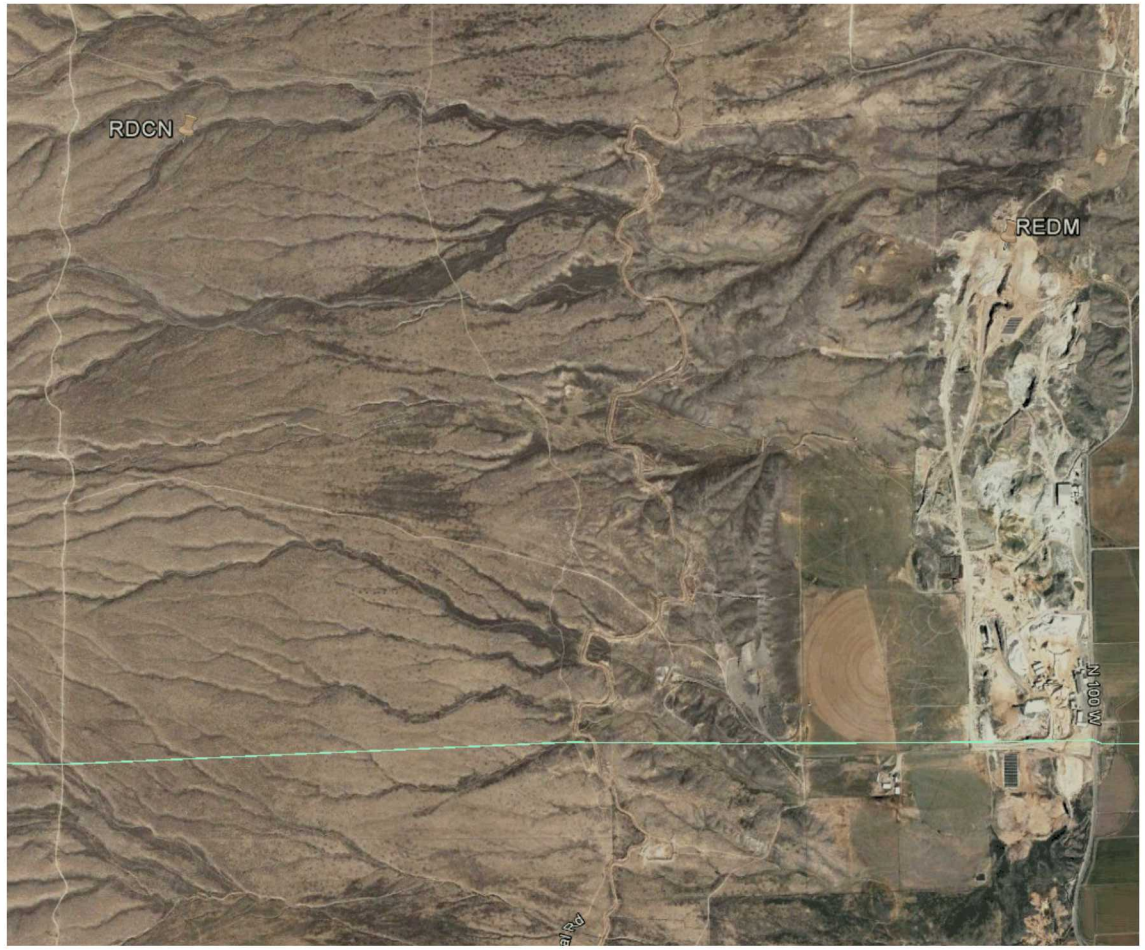
Stacking of Redmond Mine Data for the six permanent sites

Onboard Algorithm Implementation

- Implemented and tested Correlation Algorithm in Simulink for seismic vertical channel
- Implemented and tested STA/LTA algorithm in Simulink for seismic and acoustic
- Ported Simulink Algorithms to Platform using MatLab Code Generation
- Profiled power consumption of unit to proper spec battery and solar requirements

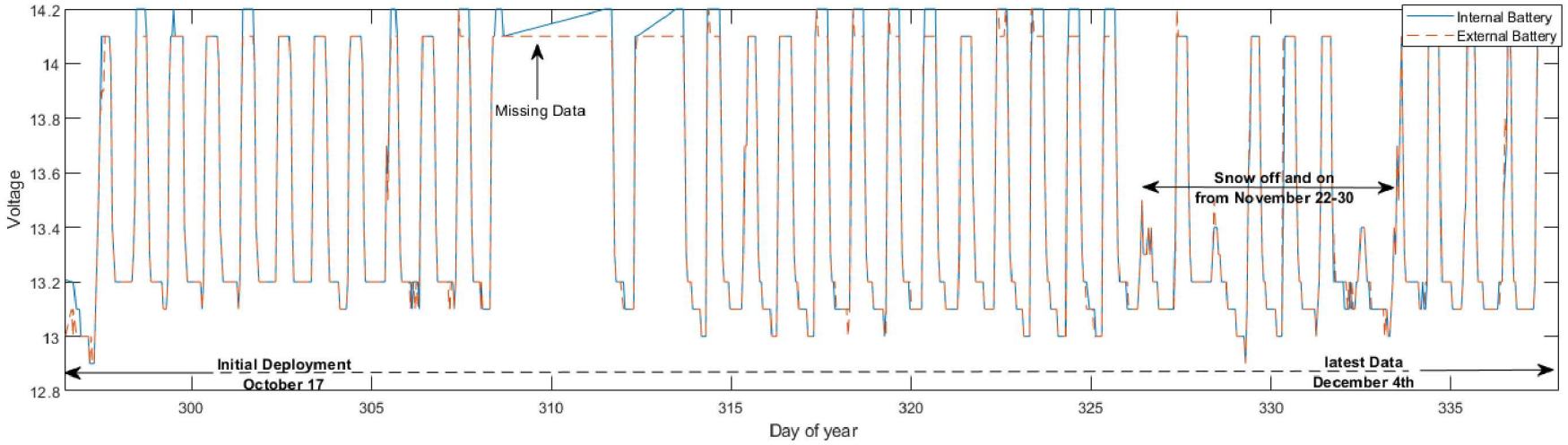


Field Testing



Field Testing Results

- System is robust to adverse weather conditions
- Recorded data tracks that obtained with standard equipment at the same location
- Communication pathway with remote system is robust
- System was capable of detecting events using STA/LTA filter and reporting daily detections via email



Conclusions and Ongoing Work

Completed

- Design and construction of a set of four autonomous platforms has been completed. Field testing of these systems shows that they are robust to adverse weather and capable of unattended operation for long periods of time.

In Progress

- Laboratory development of processing algorithms capable of running on the autonomous platforms. We plan to inject Redmond Mine data into the units using a function generator and evaluate performance.
- Field testing of units continues, both at Redmond Mine and at Kirtland AFB.

Future Work

(1) Complete laboratory development of onboard algorithms
(2) Field deploy units to test onboard algorithms and for seismoacoustic array processing
(3) Add direct inter-node communication ability