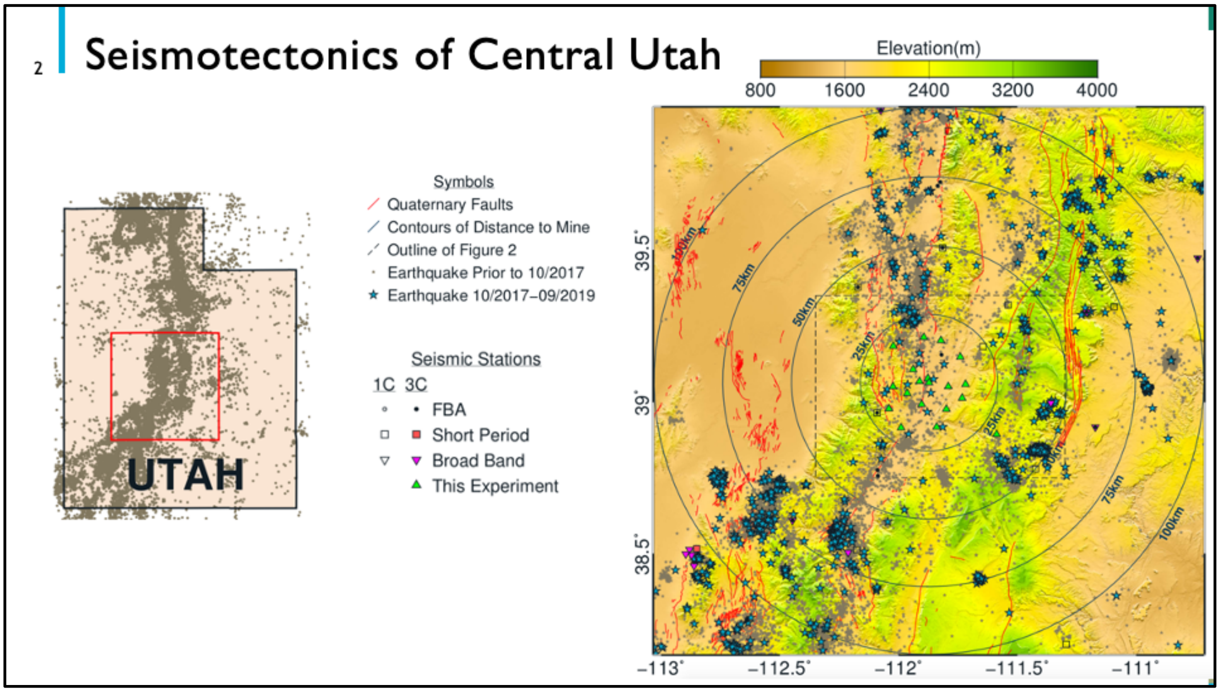
From October 2017 until July 2019, we collected seismic and infrasound data emanating from Redmond Salt Mine, central Utah, where blasting activity occurs within an extensive underground tunnel complex several times per week as part of normal mine operations.

Our goals for this experiment were to:

1. Collect co-located seismic and infrasound data near the mine complex to determine if the underground explosions were generating infrasound signals radiating from the surface above the explosions or out through the tunnels themselves.
2. Characterize the seismic and infrasound signals recorded during this experiment to determine any implications for near-source monitoring campaigns.
3. Collect a dataset that was rich in both low-magnitude explosive sources and earthquakes at near local (< 20km) distances from which we can test and design discrimination methods for small events recorded at near offsets.

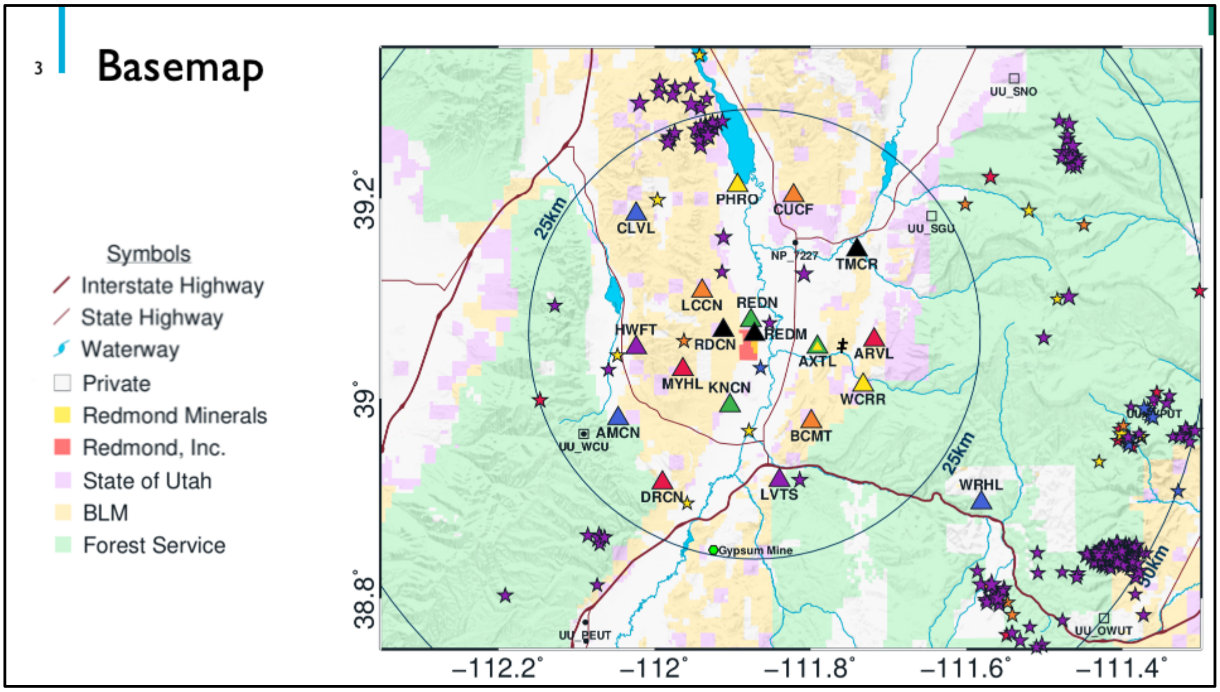
This presentation focuses on the first of these two objectives and briefly touches on the third.



Redmond Salt Mine is located within the band of active seismicity that occurs along the Wasatch Front in Central Utah that marks the transition from the basin and range tectonic province to the West from the Colorado Plateau to the East. The image on the left shows this band of seismicity running through central Utah. On the right is a seismotectonic map of the region near our study area, centered on the location of Redmond Salt Mine. Concentric circles in the image on the right show distance to the mine, brown stars show the locations of historical Utah earthquakes, while the blue stars show the location of earthquakes and mining-related events that occurred during this experiment. Locations for these events are those reported by the University of Utah Seismograph Stations network.

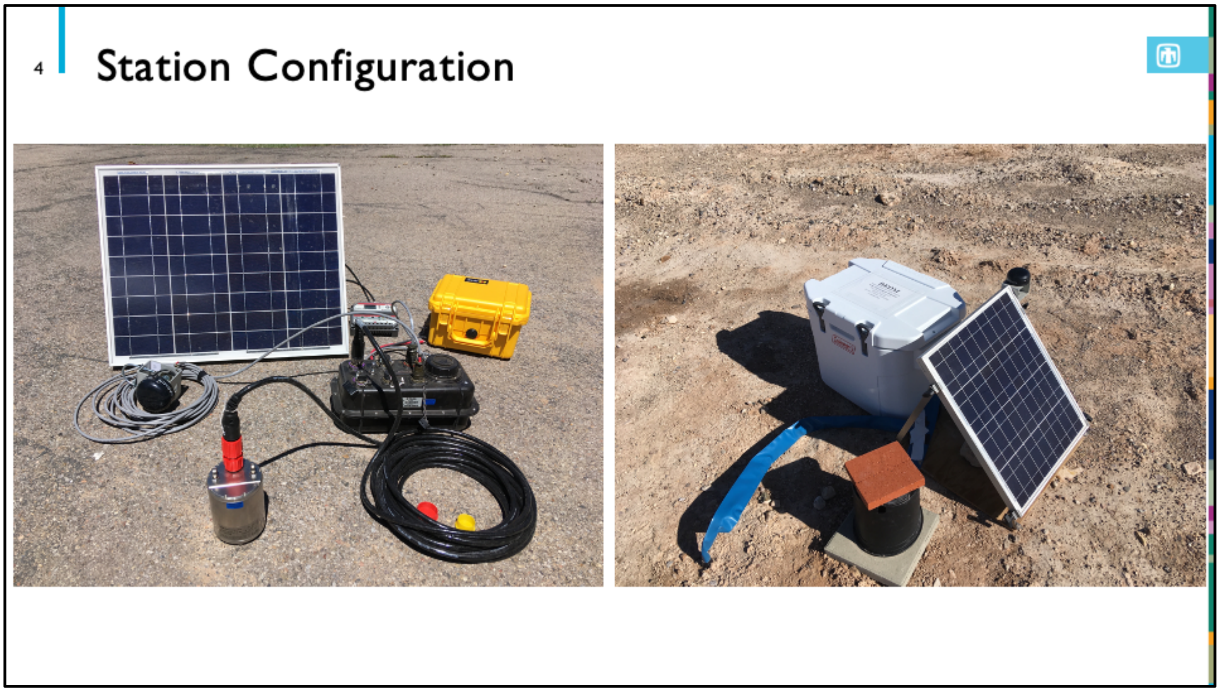
The green triangles in the image on the right indicate the permitted station locations used during this experiment. Note that, at most, only six of these stations recorded data at any given time. These stations are located, with a single exception, within approximately 20 km of the mine location, thus the explosion data recorded represents the local wavefield near the explosion locations.

The location of the mine within this band of historical seismicity means that it is also an ideal location to study and test methods that discriminate between small magnitude explosive and tectonic events at local distances.

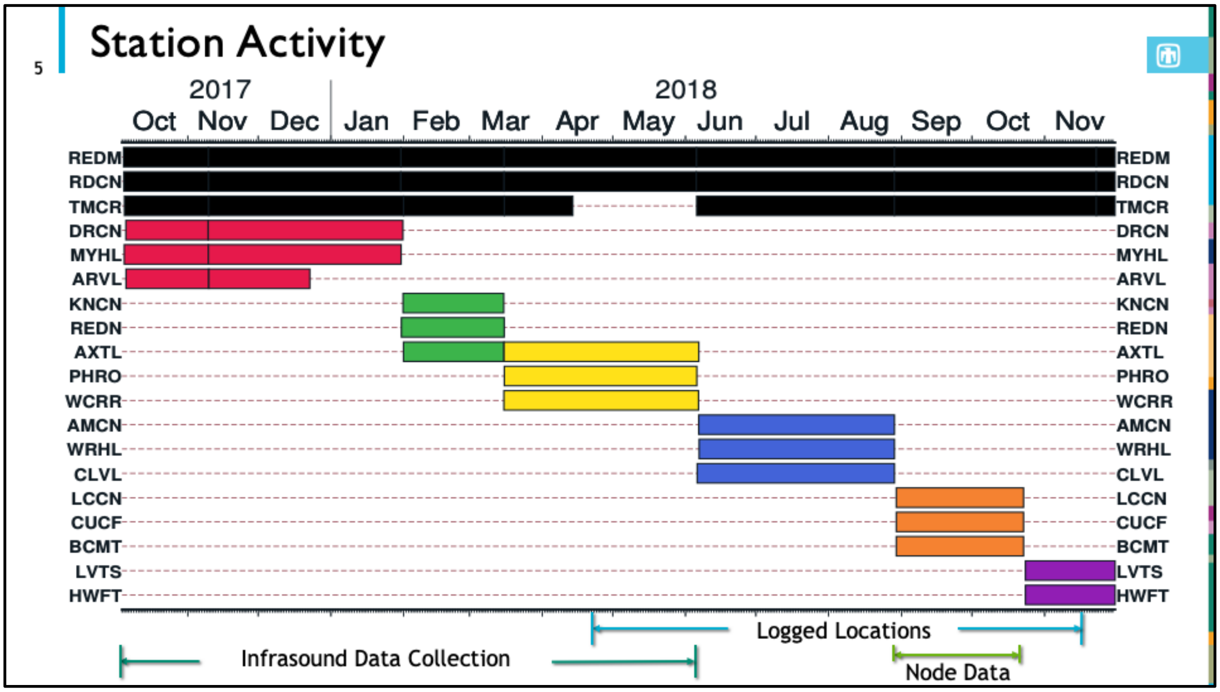


This base map, the location of which is shown by the dashed box in the right-hand image on the previous page, shows the seismic and infrasound station locations in the region near Redmond Salt mine, which is located at the center of this figure near station REDM. The coloring of the stations (triangles) and the earthquakes (stars) is such that the earthquakes recorded by each station are colored the same, as the station configuration changed throughout the experiment. For example, stations LCCN, BCMT and CUCF would have been actively recording when the orange earthquakes occurred. The black stations, REDM, RDCN and TMCR remained fixed and actively recording throughout the entire experiment.

From October 2018 until the end of the experiment in July 2019, the station locations remained fixed in order to record a series of tectonic events to help populate a discrimination dataset with appropriate events. This period, indicated by the purple events, includes two tectonic event clusters, one near (111.5 W, 39.25 N) and another near (111.9 W, 39.3 N), the first of which represents an aftershock sequence. The event clusters to the southeast of the mine at a distance of 35-50 km represent a set of mining-induced seismicity resulting from operations at coal mines in the area.



Each station consisted of a solar-charged battery for power, a Reftek 130S data recorder, a Nanometrics Trillium 120 Compact PH seismometer and a Hyperion IFS-3111 analog infrasound microbarometer (Left Figure above, IFS-3111 not shown). As deployed (right figure above) the battery, solar charger and digitizer were enclosed in a large cooler to maintain temperature stability, the Hyperion infrasound sensor was placed on a cement base and covered by an inverted planter to reduce wind noise. The Trillium seismometer was buried to a typical depth of 0.75m. This configuration is nearly identical to that used in the community-standard IRIS/Passcal temporary station deployments. Sample rates used throughout the experiment were 250 Hz, and the stations recorded data continuously.



This image presents the timeline of the early part of the experiment, from October 2017 to Dec. 2018. Colors for each station correspond to the colors of the station locations shown in the base map. In contrast to the period from 10/2018 until the end of the experiment in 7/2019 described above, during this first part of the experiment tectonic activity was relatively low: 50 tectonic events were recorded from 10/2017 through 11/2018 compared to 300 from 12/2018 until 7/2019.

The early part of the experiment provides a detailed examination of the mining explosions. From the start of the experiment until June 2018, we recorded infrasound signals radiating from the mine. In addition, we were able to obtain detailed log information from the mining operators for the period of May 2018 until November 2018, which when combined with detailed survey information allow us to precisely determine the location of the mining blasts within the mine. Thus the experiment self-organized into three distinct periods:

1. Oct. 2017 – June 2018 during which infrasound signals radiating from the underground mine complex were recorded.
2. May 2018 – Nov. 2018 during which we were able to obtain detailed ground-truth information on the location of the underground mining blasts
3. Dec. 2018 – July 2019 during which a large number of tectonic events were recorded.

The rest of this presentation will focus on analysis of the data collected during the first period.

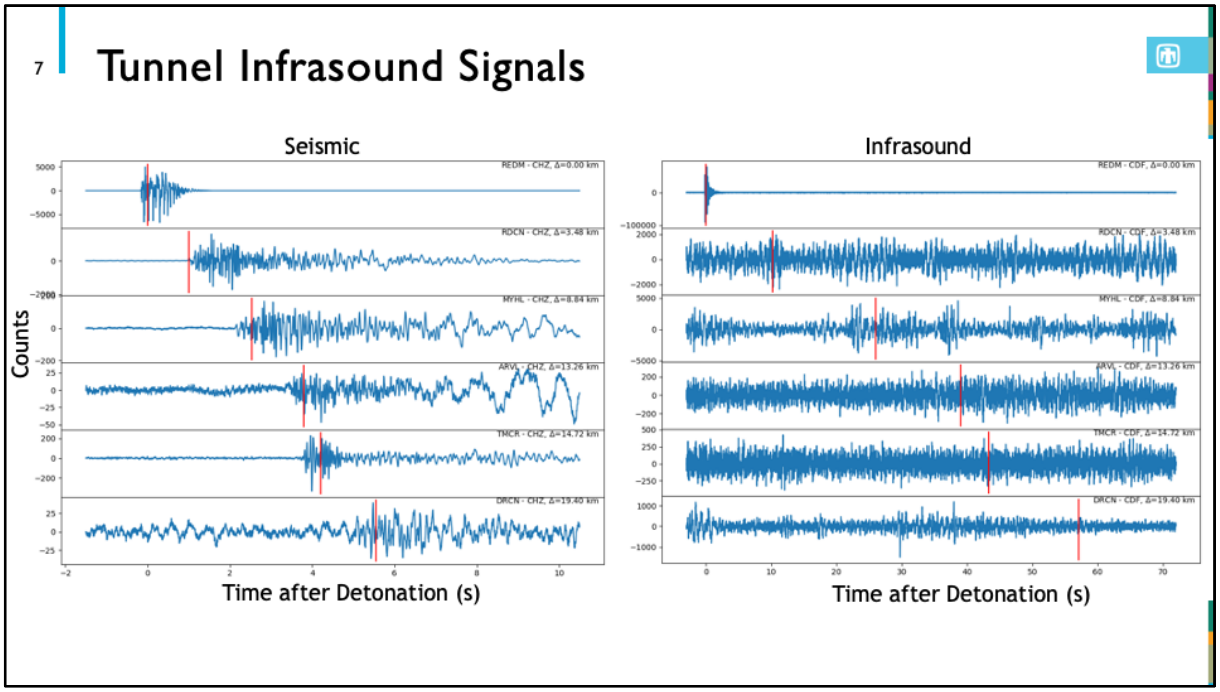
6 Explosion Source Properties

Explosion Properties

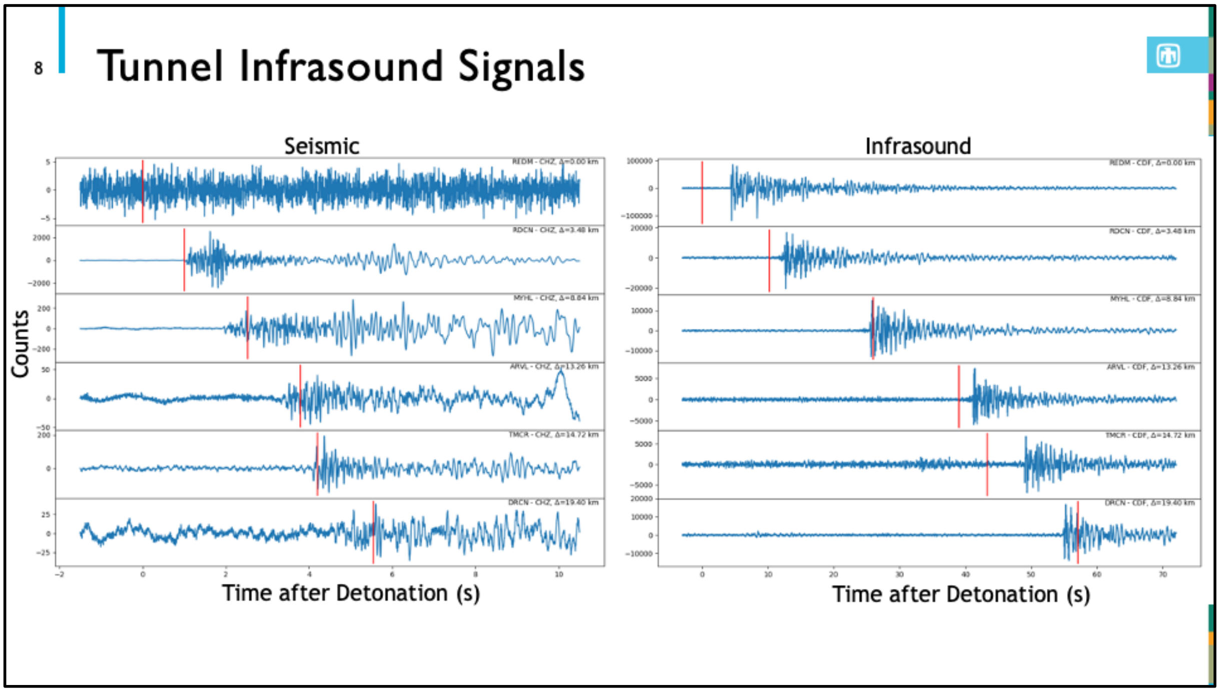
- Several different explosion types:
    - Face, Lifter, Rock, Lead and Asperity
- Face shots most common and are typically 600-800kg TNT equivalent
- Explosives are emplaced in a grid of 14 by 12 holes drilled into the face
- Each explosion lengthens the tunnels by approximately 15 feet
- Detonation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

Blasting occurs at a variety of locations within the mine, ranging in depths from 20 feet to 600 feet below the surface. The mine is organized into five levels: AA, A, B, C, D, from shallowest to deepest. Within each level, blasting occurs at from 1 to five different locations. During normal operations, blasting operations occur four nights a week with an average of 3 explosions per night. During the course of the experiment, we recorded signals from approximately 1000 separate explosions, with 333 of them occurring during the period of infrasound recording.

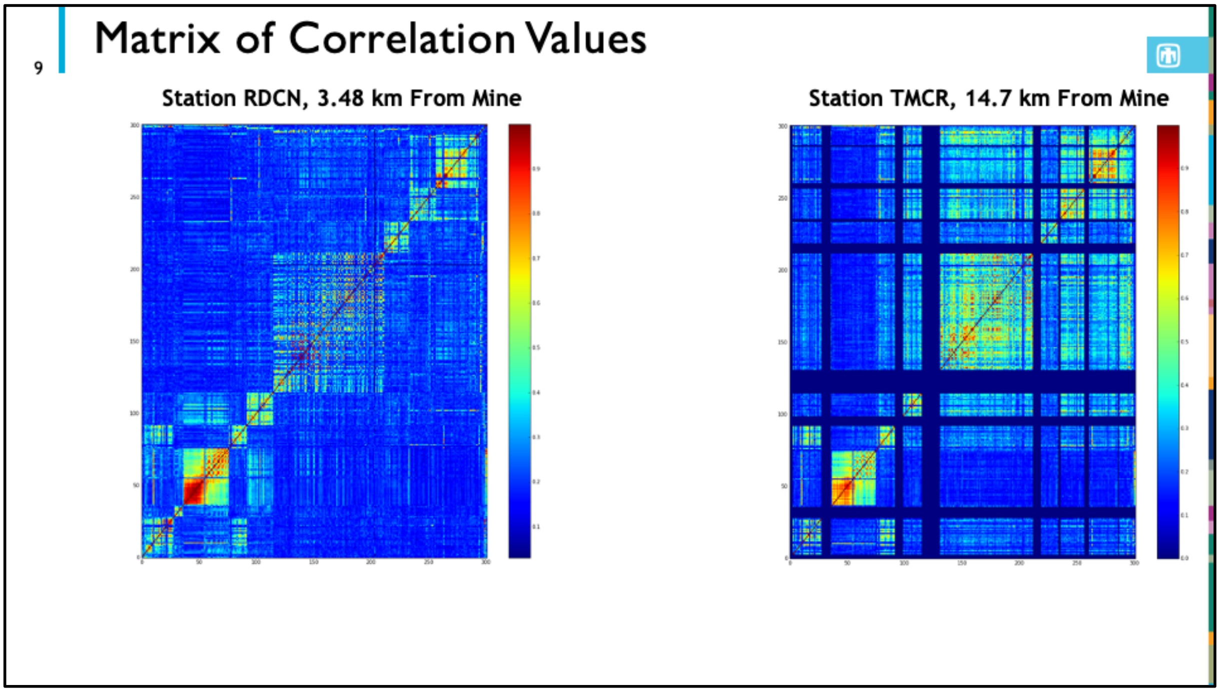
The structure of the mine consists of s series of interconnected tunnels at each level, with more extensive tunnel structures occurring at the shallower, oldest levels. The mined tunnels are roughly square in cross-section, with typical dimensions of 40 feet by 40 feet. Mining of each tunnel occurs in two stages, with the top half of the tunnel being excavated first, followed by the bottom half in a series of “lifter” explosions.



For the majority of the recorded events, the infrasound data streams contain no obvious arrivals. The red lines in the above plots are predicted arrival times for both the seismic (left) and infrasound (right) arrivals, assuming an origin located at the northern end of the mine, and seismic and infrasound propagation velocities of 3500 m/s and 340 m/s respectively. There are no obvious arrivals present within the infrasound data—the distinct arrival at station REDM is attributed to vertical motion of the infrasound sensor resulting from the seismic arrival.



However, for roughly 15% of the mining explosions strong infrasound arrivals are present in the data recorded at all the active stations. The presence of these arrivals is not correlated with any particular atmospheric condition, and from investigating the rough proportions of events occurring at the shallowest layers (AA and A) within the mine during the period for which we have access to locations logged by the mine operators, these signals seem to have originated from acoustic energy that radiates out of the mine portals. The delay between the predicted infrasound arrival and the observed infrasound arrival at station REDM represents the time taken for the acoustic energy to travel to the mine portal—located 500m away from station REDM– and through the atmosphere to that station. The seismic arrivals show considerable inter-station differences, attributed to the complexity of the seismic wavefield through heterogenous material, and specific site site responses. In contrast, the infrasound signals have a much more uniform response across the stations. This observation indicates that at local distances infrasound signals may be more useful for determining source properties than the seismic signals, which are more sensitive to propagation effects.



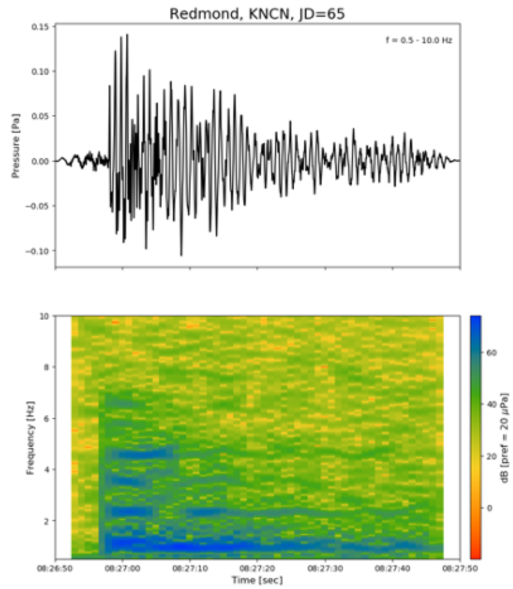
The conclusion that the seismic signals contain prominent propagation effects is supported through waveform correlation analysis. If arrivals for a series of events are correlated with each other for a particular station, they can be clustered into groups. Comparing these groups to the logged locations for arrivals from logged events, indicates that these clusters correspond to individual mining locations within the mine. Thus the seismic signals are easily used to distinguish these locations. If the correlation values are plotted in a matrix form, the above images are generated. The block-like groups of high correlation represent events that occurred in the same region within the mine. Note that for station TMCR (right) the dark blue bands of zero correlation result from a station outage from April to June 2018. Strong infrasound arrivals across the stations as shown in the previous slide correspond to single event clusters. This observation indicates that only the explosions occurring in the shallow levels of the mine generate infrasound signals exterior to the mine, while the acoustic energy generated by deeper events remains trapped with the mine structure.

10

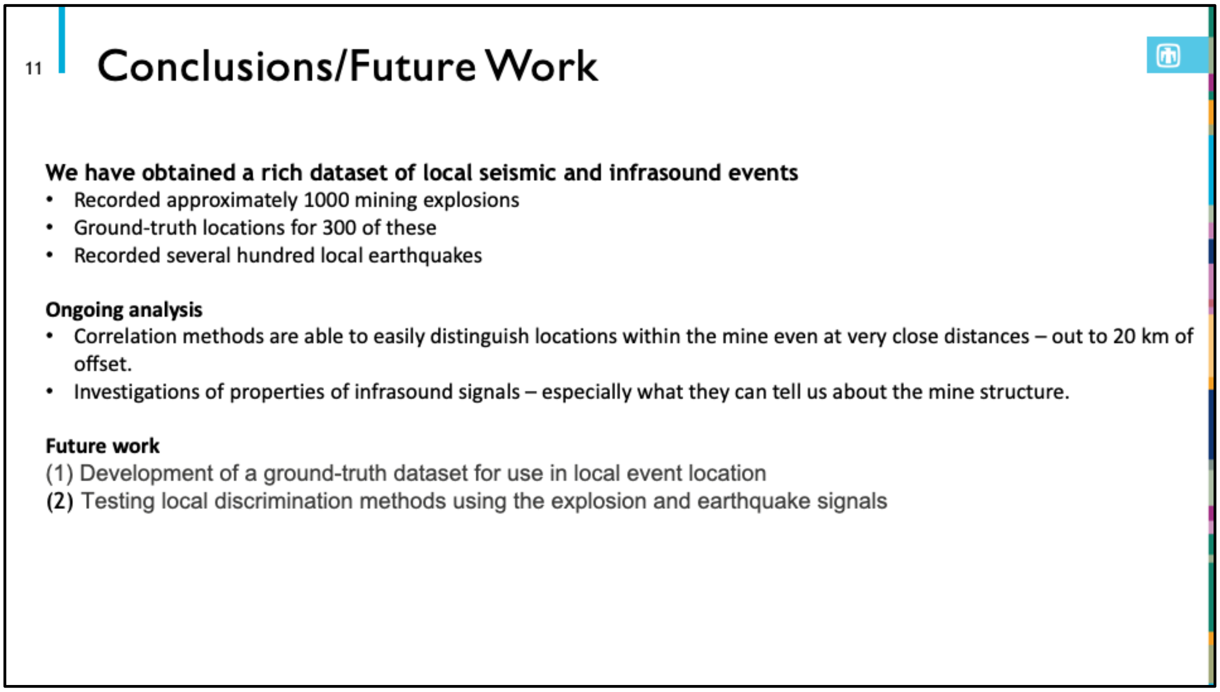
Tunnel Infrasound Signals

The recorded signals contain an interesting harmonic structure

- This structure is consistent with a model of a vibrating air column in a long tube.
- Comparing the observed spectral peaks to those predicted using a simple pipe model for the mine indicates a tunnel length of approximately 700 feet.
- This length is consistent with the length of the tunnel segment located immediately adjacent to the mine portal indicating that acoustic energy gets trapped within this tunnel and resonates along the tunnel length



The infrasound signals exhibit a harmonic structure similar to that expected for a column of air vibrating within a tube. The frequencies present in these signals is consistent with a model for infrasound generation in which the observed signals are caused by radiation of energy resonating in the tunnel immediately adjacent to the mine portal. Thus these signals can be used to infer properties of the mine structure.



We have completed data collection at Redmond Salt Mine. Future efforts there will focus on different experimental designs. We have assembled three datasets each of which has a unique focus: an set of infrasound signals radiating from the mine structure; a ground-truth dataset which contains accurate locations of events recorded locally; and a set of tectonic and explosive seismic signals useful for developing local discriminants. Future analyses will focus on in-depth study of these datasets including numerical modeling of the infrasound arrivals, testing of local event location methods and the development of discrimination methods useful for separating explosive from tectonic events as recorded locally.