Seismology (pronunciation: /saɪzˈmɒlədʒi/; from Ancient Greek σεισμός (seismós) meaning "earthquake" and -λογία (-logía) meaning "study of") is the scientific study of earthquakes and the propagation of elastic waves through the Earth or through other planet-like bodies. The field also includes studies of earthquake environmental effects such as tsunamis as well as diverse seismic sources such as volcanic, tectonic, oceanic, atmospheric, and artificial processes such as explosions. A related field that uses geology to infer information regarding past earthquakes is paleoseismology. A recording of earth motion as a function of time is called a seismogram. A seismologist is a scientist who does research in seismology.

Types of seismic wave

Three lines with frequent vertical excursions.

Seismogram records showing the three components of ground motion. The red line marks the first arrival of P-waves; the green line, the later arrival of S-waves.

Seismic waves are elastic waves that propagate in solid or fluid materials. They can be divided into body waves that travel through the interior of the materials; surface waves that travel along surfaces or interfaces between materials; and normal modes, a form of standing wave.

Body waves

Surface waves

Normal modes

This presentation focuses on seismic and infrasound signals from the following three types of mining operations:

Coal overburden casting (Black Thunder, WY) where explosions are designed to remove overburden to expose coal;

Rock fragmentation for copper recovery where moderate sized explosions are

designed to break the rock for further processing; and

Rock fragmentation in hard rock for iron recovery where large scale explosions are used to pulverize the taconite for further processing. Eachmine has distinctive blasting practices that are reflected in regional seismic and infrasound signals that are

illustrated in this paper.

In all three types of mining operations, peak amplitude of regional seismic signals is independent of the total explosive weight (Figure 1 coal cast blasts, Figure 2 taconite(iron) fragmentation, and Figure 3, right, copper fragmentation blasts). In-mine peak amplitudes are also independent of total explosive weight (Figure 3, left). A series of contained, single-fired explosion experiments with total explosive weights from 5,000 to 50,000 lbs. were conducted in the coal mine to further investigate coupling. Regional phase amplitudes of Pn, Pg and Lg increase with a power law relation to total explosive weight (Figure 1, ~Wb).

Figure 1: Peak Pg amplitudes observed at array element 03 of PDAR (360 km range) from contained singlefired explosions, delay-fired cast blasts and delay-fired coal shots

Figure 2: Peak P and Rg amplitudes observed at EYMN (Ely, Minnesota) from taconite fragmentation

explosions approximately 110 km to the southwest of the station.

Figure 3: Peak amplitudes of in-mine recordings at Morenci are compared to total amount of explosives used in copper fragmentation blasts (left). Peak Pg, Lg and Rg amplitudes observed at the regional station TUC plotted against total amount of explosives used in the Morenci copper fragmentation explosions (right)

Figure 4: The three components of the equivalent mining explosion source model are represented pictorially. They consist of (a) the directly coupled energy from the contained explosion modeled as a Mueller-Murphy source function, (b) vertical spall due to the tensile failure of near-surface materials and (c) horizontal spall accompanying cast blasting when overburden is cast horizontally into a pit.

Figure 5: Spall mass (per hole) for the taconite hard rock explosions (open diamonds) and a single coal cast blast (star) was estimated from blasting logs. These empirical estimates from mining explosions are compared to the Viecelli and Sobel spall mass scaling relations developed for underground nuclear explosions.

Figure 6: The mining explosion source model (Figure 4) was used to produce synthetics for a distance and crustal velocity model appropriate for EYMN. Synthetics were produced for a number of mining explosions of different average charge weight per borehole. Peak amplitudes of the synthetics are compared to the observations from the same explosions.

Figure 7: The mining explosion source model was also used to compute synthetics for the large-scale cast blasts. The focus in this modeling exercise is on the long period surface waves

Figure 8: Mining explosions from the hard rock copper mines in southeastern Arizona generate infrasound signals as exemplified by the records from DLIAR in Los Alamos (left). Ground truth for this event was provided by close-in seismic and acoustic records of the blast (left, inset). Frequency wave number estimates were used to make the back azimuth estimate shown to the right.

Figure 9: Infrasound (channels 1,2, 3) and seismic data (channel 4) from a seismo-acoustic station installed outside El Paso, Texas (Ft. Hancock). Each horizontal section represents 10 minutes of data. This seismo-acoustic signal that extends for over 30 minutes represents the explosion and burning of a natural gas line in New Mexico (photo- Terry Wallace, University of Arizona).

Figure 10: The details of the infrasound (channels 1-3) and seismic (channel 4) signals from the gas explosion are shown to the left. These signals are compared to close-in seismic signals of the blast shown to the right (courtesy of T. Wallace). Both the close-in seismic and the infrasound signals suggest a complex source function for the initial explosion. The seismo-acoustic station at Ft. Hancock has porous and slow velocity alluvium at the surface that may be responsible for the strong coupling between the infrasound and seismic channels.

**CONCLUSIONS AND RECOMMENDATIONS  
*Seismic***1. Peak seismic amplitudes from delay-fired mining explosions show little relation to explosive yield.  
2. Single-fired, contained explosions generate regional seismic waves with an amplitude scaled by  
explosive weight, W0.84.  
3. Source models for mining explosions replicate the insensitivity of peak amplitude of regional phases to  
total explosive weight although there is some indication that the peak regional amplitudes may be  
related to the weight of the simultaneously detonated explosives, possibly a single borehole.  
4. Mid-period (2-12 s) surface waves are observed from large scale cast blasts and reflect the large source  
duration of such explosions.  
5. Blasting practice varies greatly between mines and within mines and in-mine instrumentation may be  
required to provide ground truth for regional seismogram interpretation.  
***Infrasound***1. A small percentage of mining explosions are observed to have infrasound signals.  
2. The presence or absence of regional infrasound signals is related to event size and propagation path  
effects.  
3. Shallow explosions may produce infrasound signals but no regional seismic signals.  
4. Infrasound signals may document source duration.