Acoustic Emission Investigation

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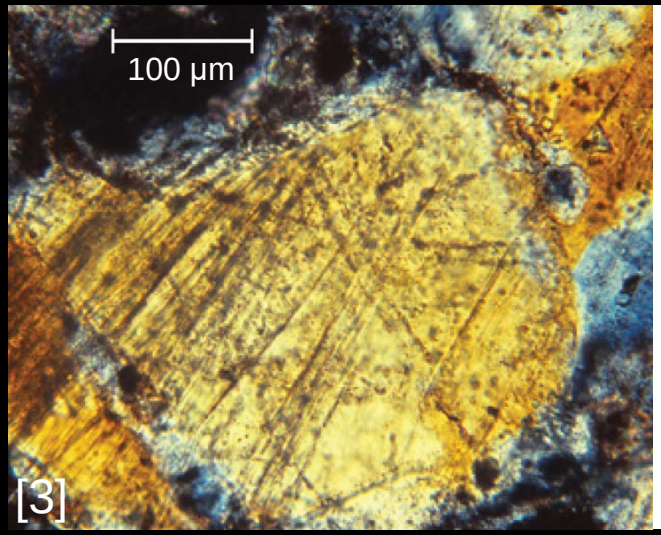
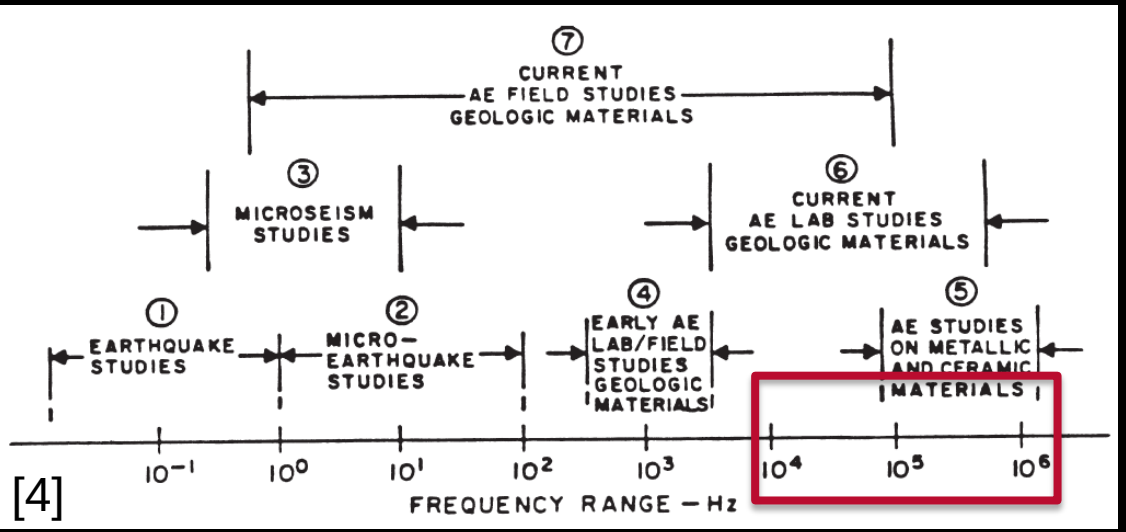
What can acoustic emissions tell us?

Introduction

Background

- **Acoustic emission (*n*): “a transient elastic wave generated by the rapid release of energy in a material” (Lockner, 1993, p. 883).**





Introduction

Background

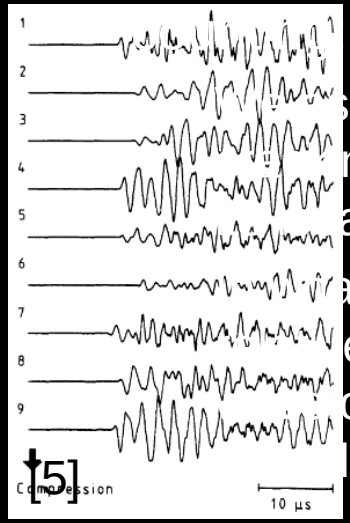
Full Waveform

- Analysis

Rationale for pursuing event

Hypocenter Location

Event Counting



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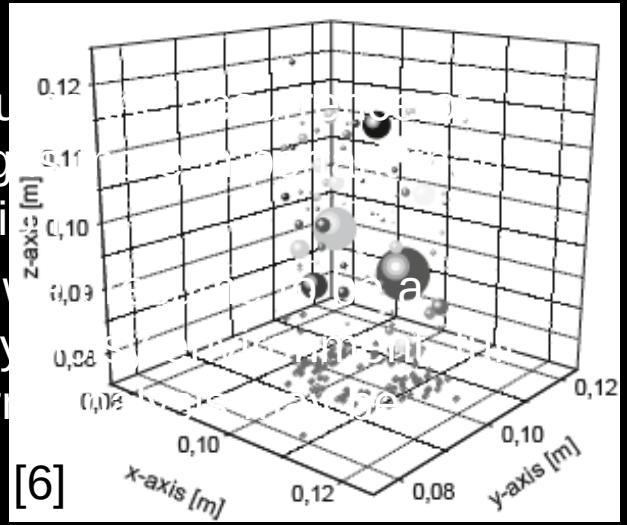

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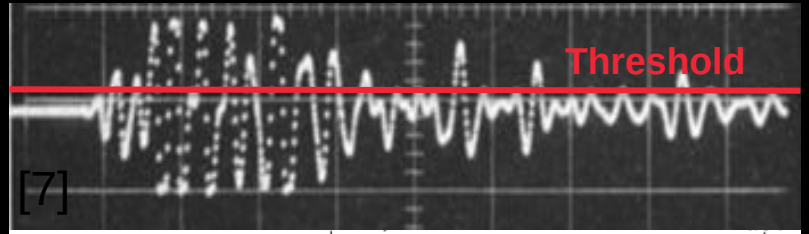

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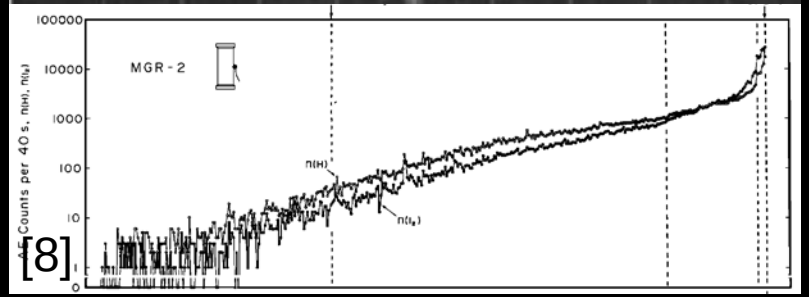

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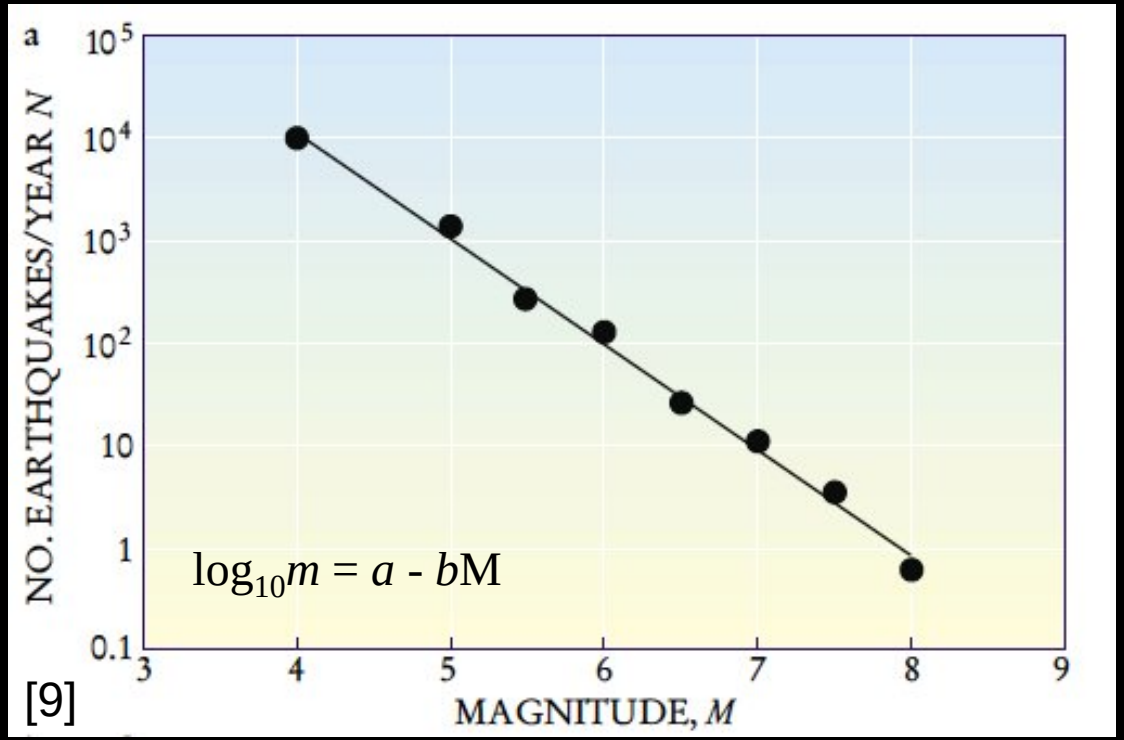
Research Plan

The Big Question

- **If we were to develop an instrument designed to monitor subsurface acoustic emissions, what would we want to know beforehand?**
  - How do we acquire acoustic emission data?
  - How does strain rate affect acoustic emission rates?
  - How does rock type affect acoustic emission rates?
  - How significant is attenuation?
  - How can we predict rock failure using acoustic emissions?
- **The short answer: replicate a study.**

Research Plan

Ohnaka and Mogi (1982) and b-value analysis



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High amplitude events are typically low frequency.

Low amplitude events are typically high frequency.

Therefore, changes in b-value can be observed through frequency instead of amplitude.

Research Plan

Introduction: Ohnaka and Mogi (1982) and b-value analysis

Mogi (1962)
AE obey the G-R law.

Scholz (1968)
B-value changes are dependent on the state of stress.

Ohnaka and Mogi (1981)
Ohnaka and Mogi (1982)
Frequency Dependence of the G-R Law in AE

Cai et al. (1988)
Negative b-value changes observed with increasing stress.

Rao et al. (2011)
Negative b-value changes supported as precursory failure sequence in fault associated rocks.

Research Plan

Introduction: Ohnaka and Mogi (1982)

Gutenberg-Richter Law

Mogi (1981) found that the slope of the G-R plot for AE events decreased after failure.

$$\log_{10} m_i = a - b_i \mathrm{M}$$
$$\log_{10} m_f = a - b_f \mathrm{M}$$
$$b_i > b_f$$

Amplitude-Frequency Dependency

Ohnaka and Mogi (1981) hypothesized that the number of high-amplitude events is proportional to the number of low-frequency events.

$$\log_{10} m_H \ \alpha \ \mathrm{n(L)}$$

Using AE Frequency to Predict Failure

Since there is an observed shift in amplitude distribution before failure, observing the relative abundance of low-frequency AE events over time could be used to predict failure.

$$\frac{\mathrm{n(L)}}{\mathrm{n(H)} + \mathrm{n(L)}}$$

Research Plan

Procedures: Ohnaka and Mogi (1982)

Test Articles

Used cores of Shinkomatsu Andesite and Mannari Granite.

Compression and Monitoring

Stressed each core under incremental uniaxial compression at low strain rates (one to five hours before failure). Monitored AE through a pair of transducers: one high-frequency (H) and one low-frequency (L).

$$L = 30 \text{ kHz}$$
$$I_1 = 250 \text{ kHz}$$
$$I_2 = 250 - 400 \text{ kHz}$$
$$H = 1 \text{ MHz}$$

$$[L,H] = [L, I_2], [I_1,H]$$

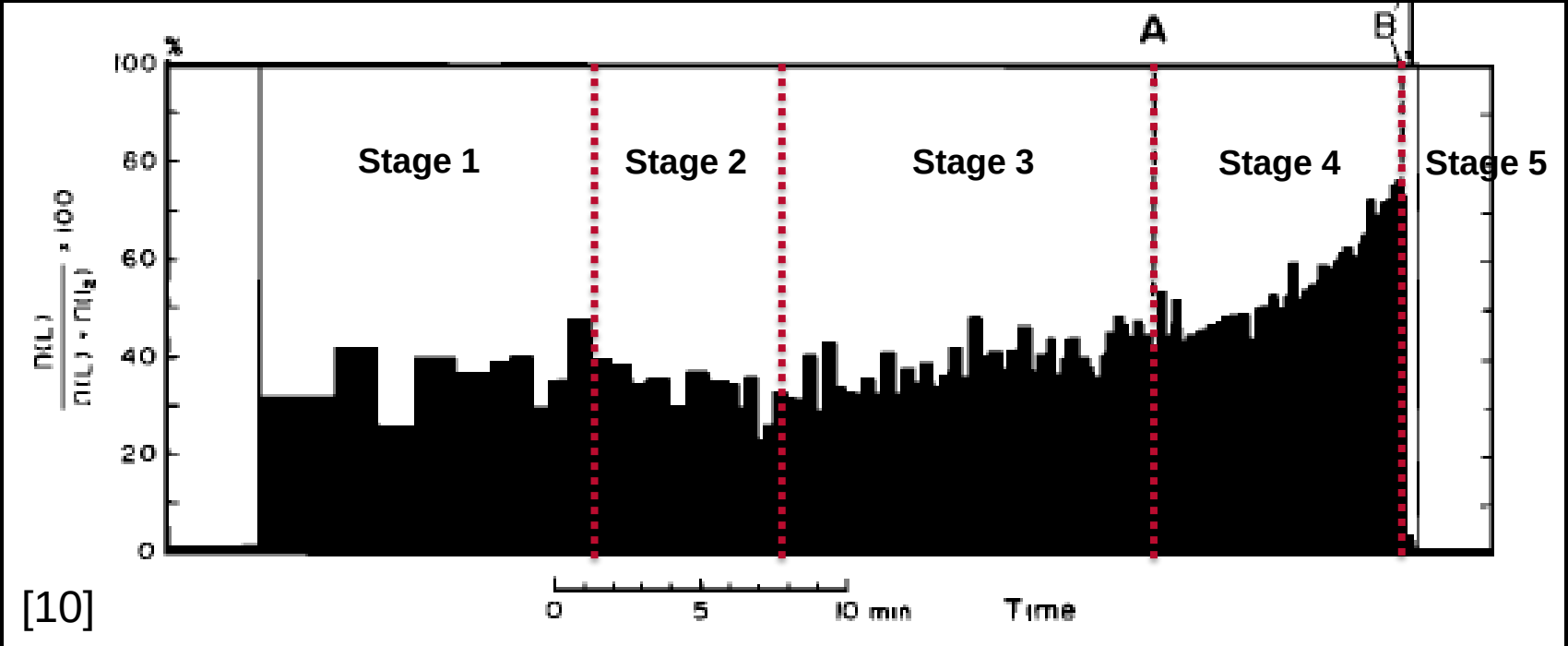
Analysis

Used time plots of the ratio below to characterize the frequency distribution of monitored acoustic emissions before and after failure.

$$\frac{n(L)}{n(H) + n(L)}$$

Research Plan

Conclusions: Ohnaka and Mogi (1981)



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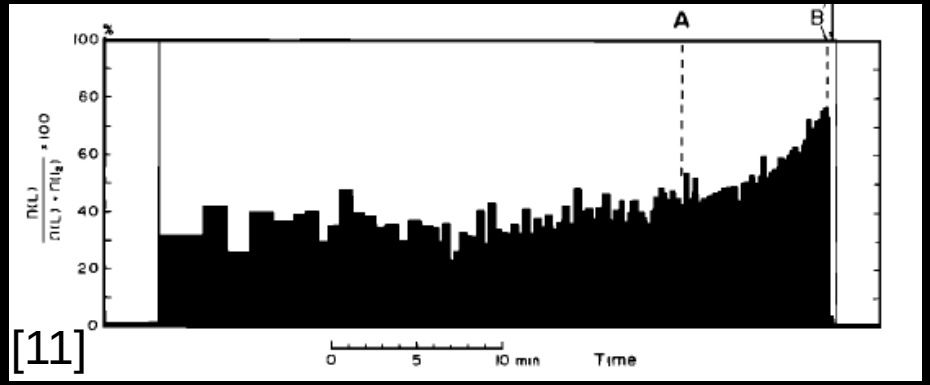
Research Plan

Why Ohnaka and Mogi (1982)?

Ohnaka and Mogi (1982)…

1. Used geological materials.
2. Analyzed emission event counts.
3. Tested a hypothesis that was relevant to our desired application.
4. Made a study that was relatively easy to expand upon.



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Research Plan

Details

1. Review literature.
2. Develop data-acquisition.
    1. Hardware
    2. Software
3. Acquire test articles.
4. Run proof-of-concept tests to validate our data-acquisition setup.
5. Acquire final test articles upon success of proof-of-concept tests.
6. Run final tests.

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Differences in experimental method

<u>Our Experiments</u>

- Full waveform sampling.
  - 16 S/s.
- Rectangular prism test articles.
- Rocks stressed for around 5 minutes.
- Sandstones and basalt.

<u>Ohnaka and Mogi (1982)</u>

- Parametric sampling.
  - 500 to 20,000 S/s.
- Cylindrical test articles.
- Rocks stressed for as much as 5 hours.
- Granite and andesite.

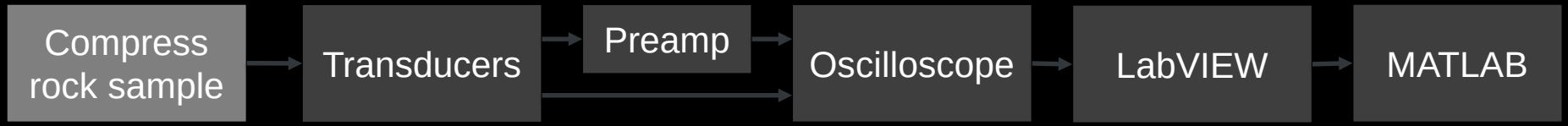
Experimental Procedures

Compress rock sample → Transducers → Preamp → Oscilloscope → LabVIEW → MATLAB

Gilson MC-500

- **Linear displacement rate between 0.014mm/s and 0.001mm/s.**

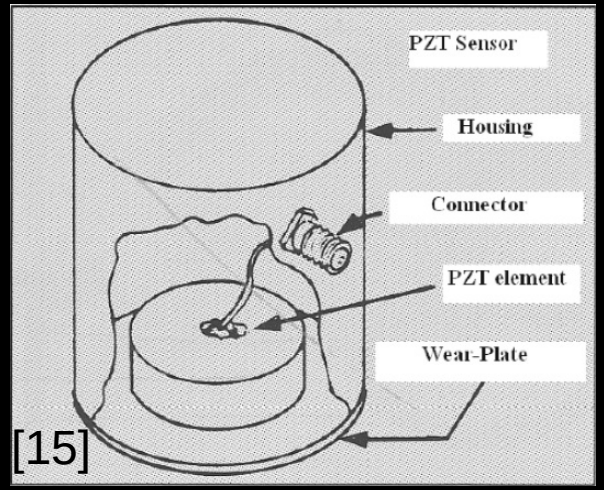
Experimental Procedures



Experimental Procedures

Compress rock sample → Transducers → Preamp → Oscilloscope → LabVIEW → MATLAB

- Transducers
  - Aerotech 1MHz and 500kHz hydrophone piezoelectric transducers
  - Silicon Gel Couplant
  - Coupled with elastic bands



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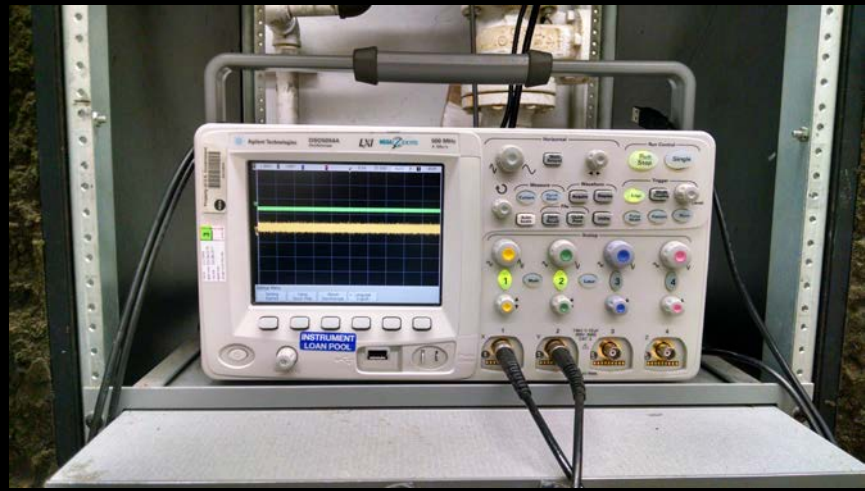
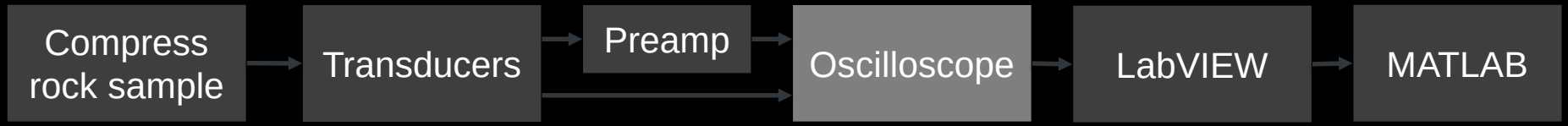
Experimental Procedures

Compress rock sample → Transducers → Preamp → Oscilloscope → LabVIEW → MATLAB

- Preamp:
  - Stanford SR560
  - Gain: $1 * 10^3$
  - Filter: High Pass 10k
  - Ch1: 1MHz transducer
- Oscilloscope:
  - Agilent DSO54045a
  - Outputs 500 sampled points per waveform



Data Capture

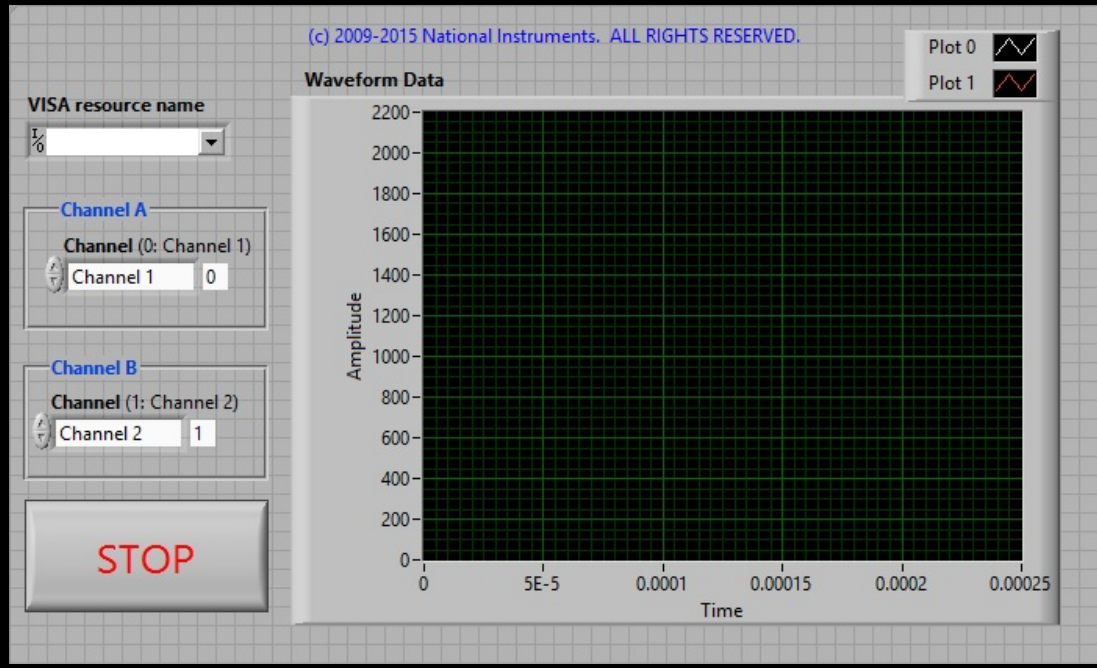


- Final Test Settings
  - Channel 1
    - 1 MHz transducer
    - 1V per partition
    - <u>50 microseconds per partition</u>
  - Channel 2
    - 500 kHz transducer
    - 100mv per partition
    - <u>50 microseconds per partition</u>

Experimental Procedures

Compress rock sample → Transducers → Preamp → Oscilloscope → LabVIEW → MATLAB

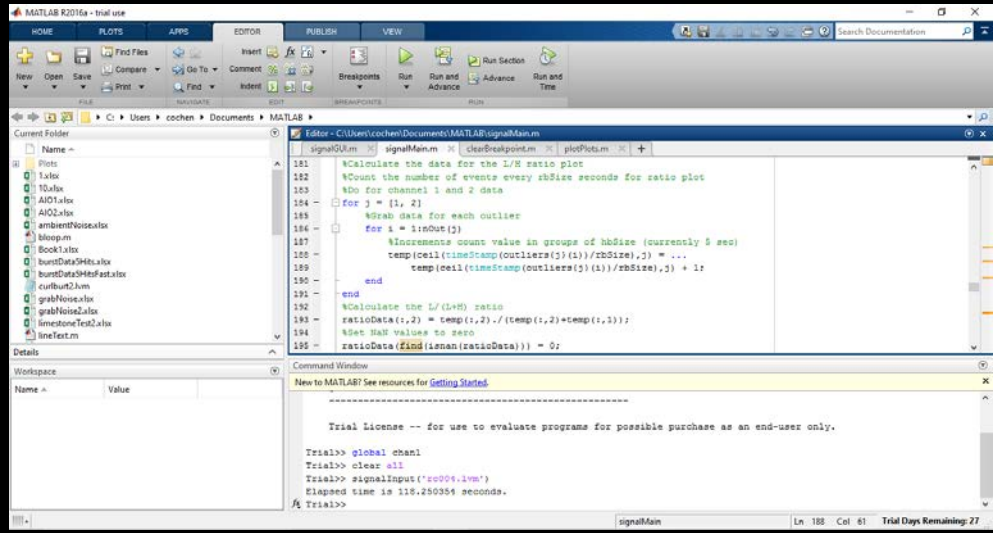
- LabVIEW 2015
  - Plots waveforms to screen and saves data points to .lvm tab-delimited files ~0.061 sec
- Sampling rate
  - 1 MHz
- Waveform sample rate
  - ~16 Hz



Experimental Procedures

Compress rock sample → Transducers → Preamp → Oscilloscope → LabVIEW → MATLAB

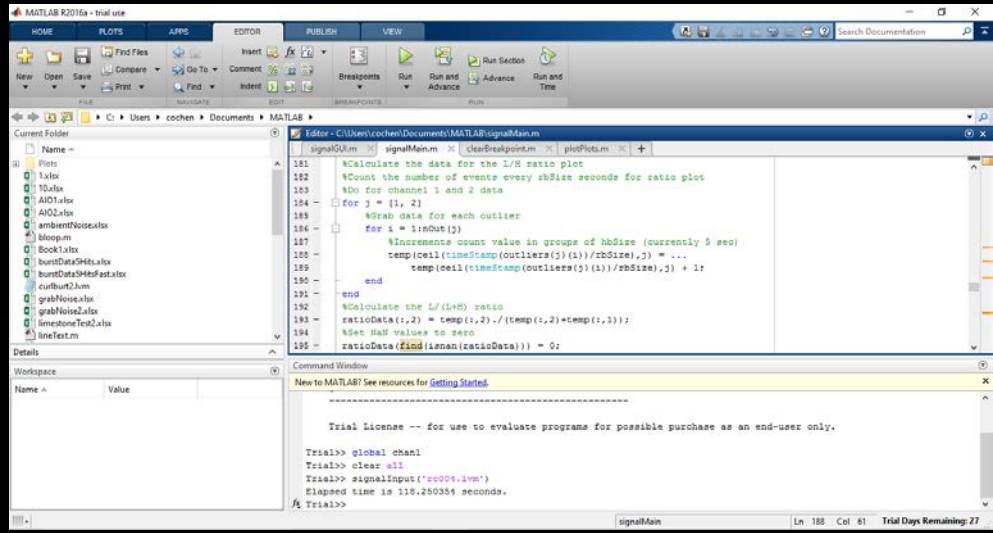
- Input: .lvm file
- Runtime: 0.3 GB file: ~10 min
  50 MB file: ~2 min
  Intel i7, 8GB RAM
- Filter data
  - 2nd order Butterworth Bandpass Filter on signals
- Identifies acoustic emission events
  - GUI
  - Statistical signal detection



Experimental Procedures

Compress rock sample → Transducers → Preamp → Oscilloscope → LabVIEW → MATLAB

- Output
  - Plot of total captured data for each channel
  - Plot of every waveform's standard deviation
  - Histogram of events over time
  - Peak frequencies over time
  - $\frac{n(l)}{n(l)+n(h)}$ ratio over time
  - Frequency vs Amplitude plot



Data Processing

Signal Detection

- Old signal-detection method
  - Analog trigger counter
  - Real time signal detection
- Our method
  - Digital post-processing
  - Take standard deviation of points
  - Set threshold
    - GUI or statistically
  - Count waveforms passing standard deviation threshold

Data Processing

Statistical method used for detecting events

- $\sigma_{AE} > \frac{\sum_{i=1}^{10} \sigma_N}{10} + 3 * \sigma_{\sigma_{N=1,2,\ldots,10}}$
- $\delta_{AE} > \frac{\sum_{i=1}^{10} \delta_N}{10} + 3 * \sigma_{\delta_{N=1,2,\ldots,10}}$
  - σ: Standard deviation
  - σ_{AE}: Standard deviation of sampled points of an acoustic emission event
  - σ_N: Standard deviation of sampled points of waveform N
  - δ_{AE}: Max-min of sampled points of an acoustic emission event
  - δ_N: Max-min of sampled points of waveform N

Data Processing

Comparing Methods (RC004)

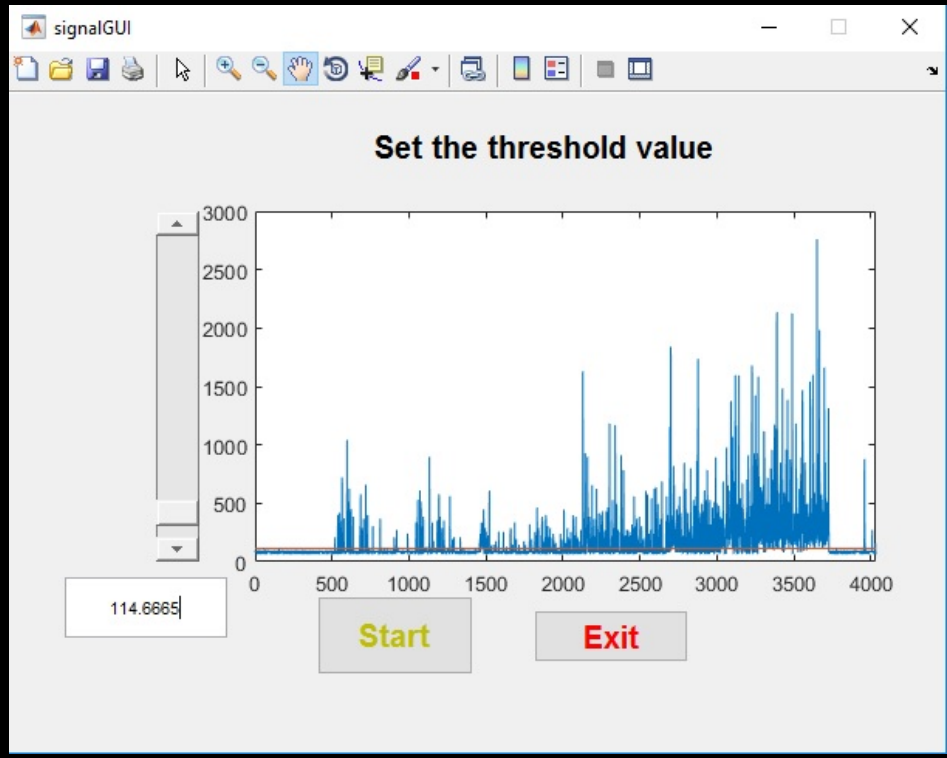
Actual events: 1073

- Standard Deviation:
  - GUI: 877
  - Predicted: 1063
- Min-Max Difference:
  - GUI: 1139
  - Predicted: 1134

Data Processing

Manual method used for detecting events

- GUI that allows user to select the standard deviation threshold used to detect a signal



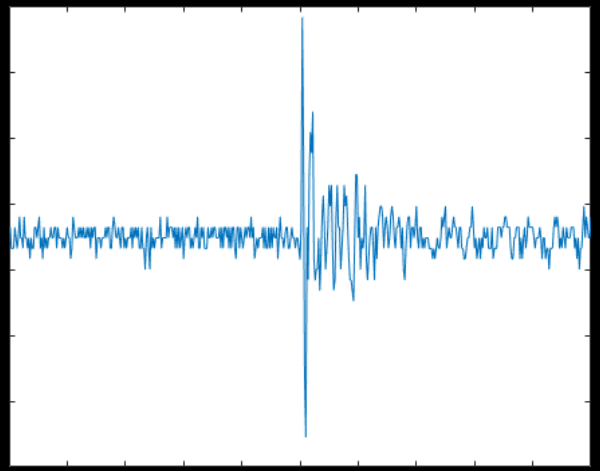
Results

Failed rocks

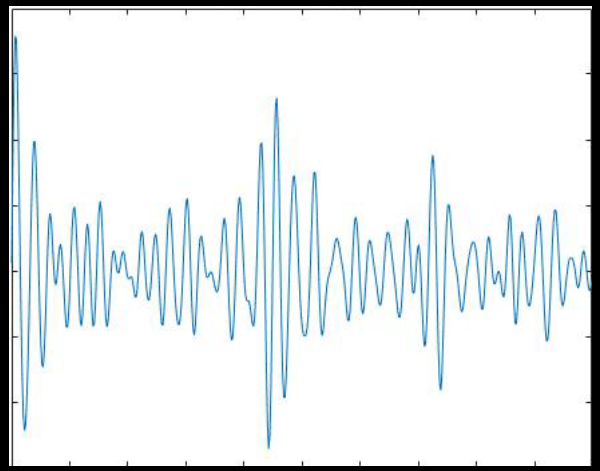
Results

Examples of burst signals

High frequency

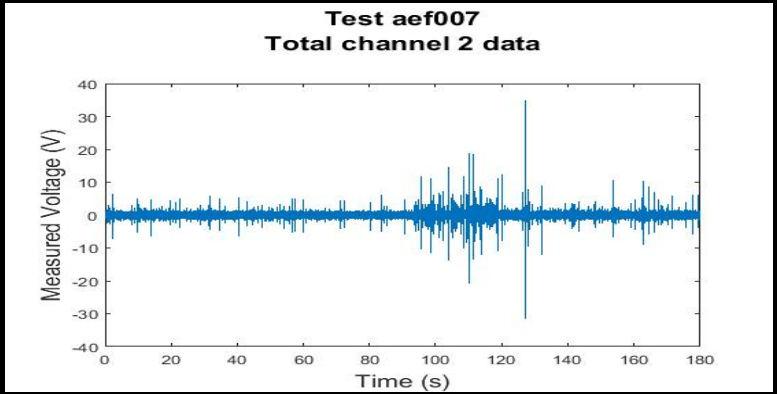


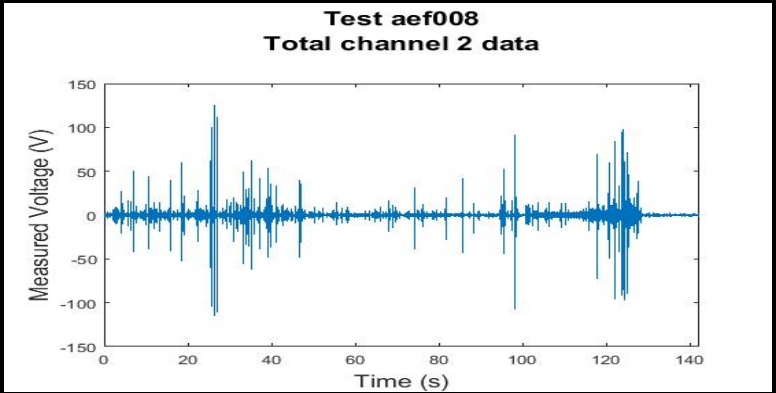
Low frequency

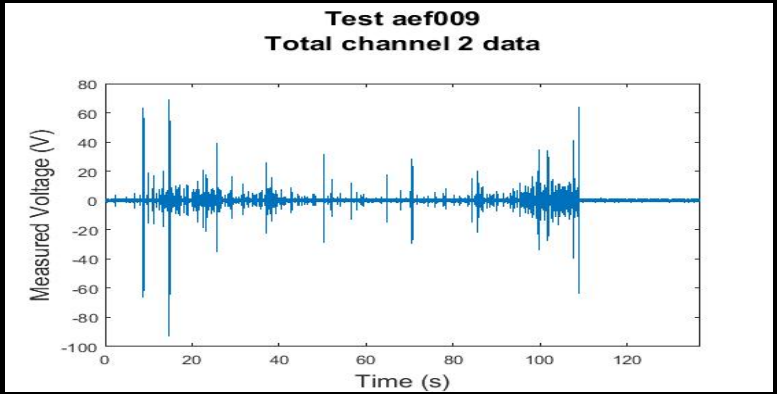


Results

Total measured signal (Low Frequency)



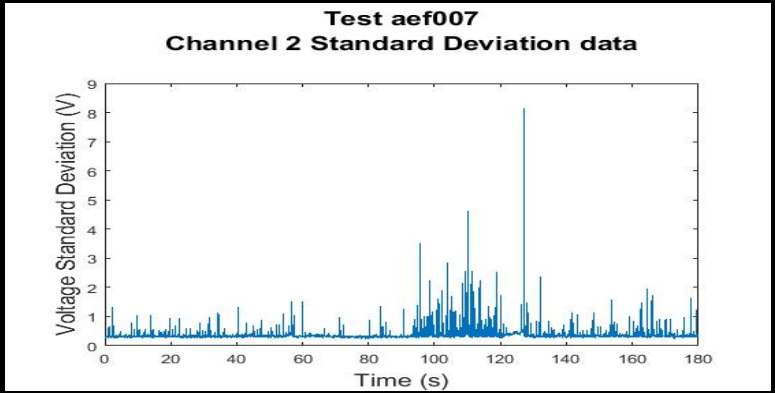


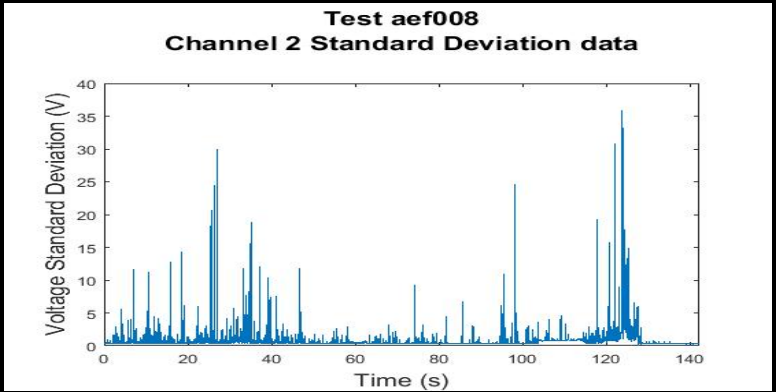


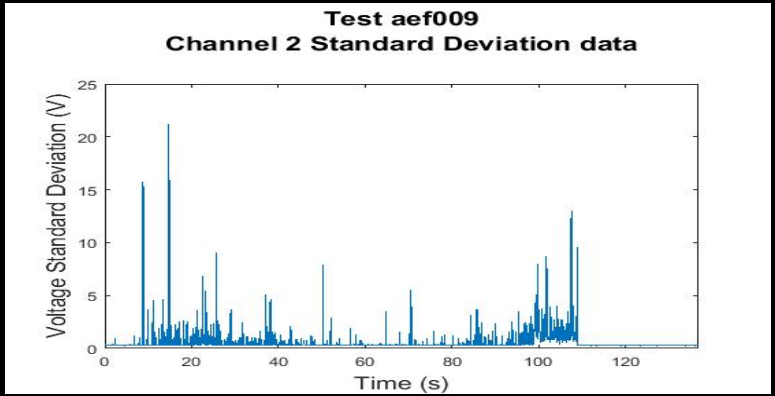
aef007 – Navajo Sandstone
aef008 – Basalt
aef009 – Grey Brown Sandstone

Results

Waveform Standard Deviations (Low Frequency)







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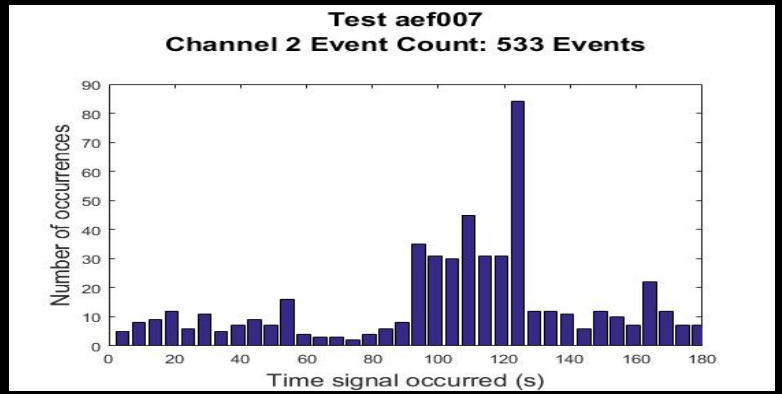
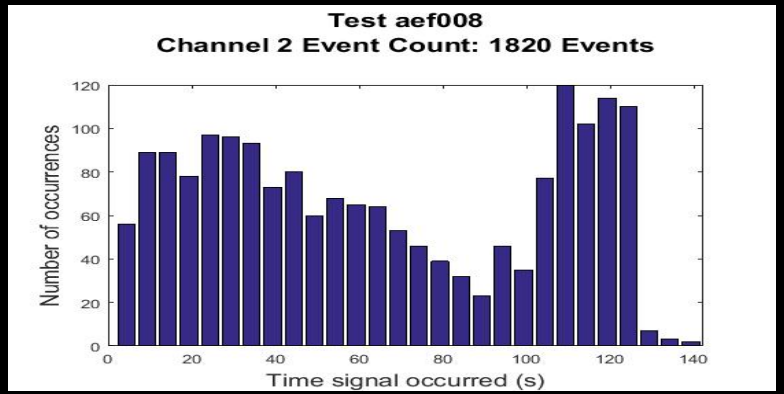
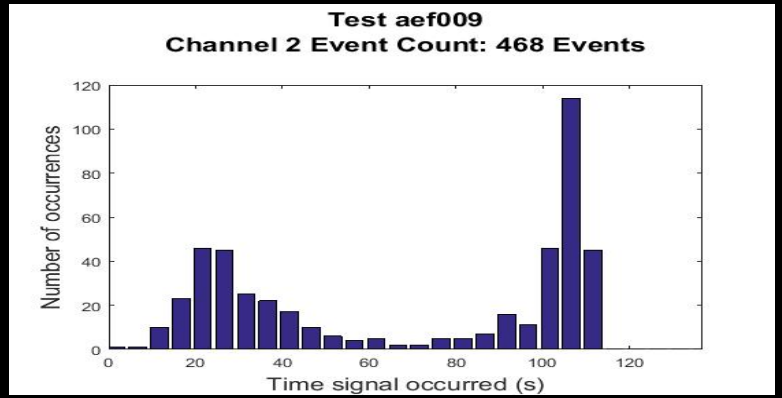
Results

Event Count Histogram (Low Frequency)







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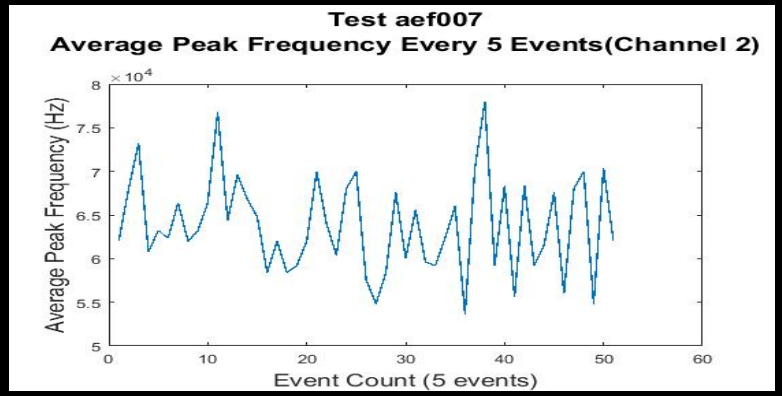
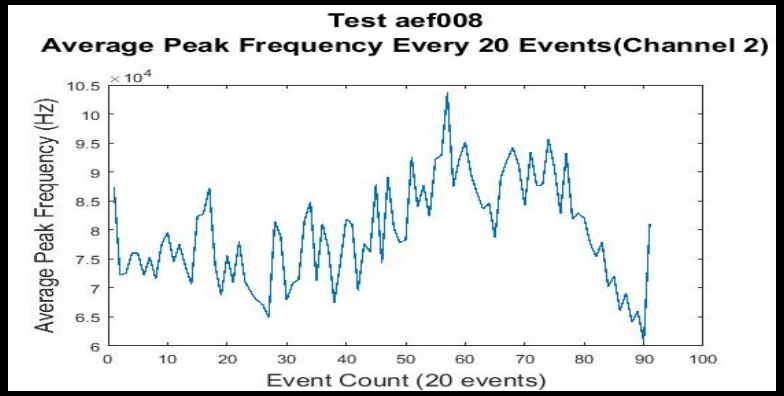
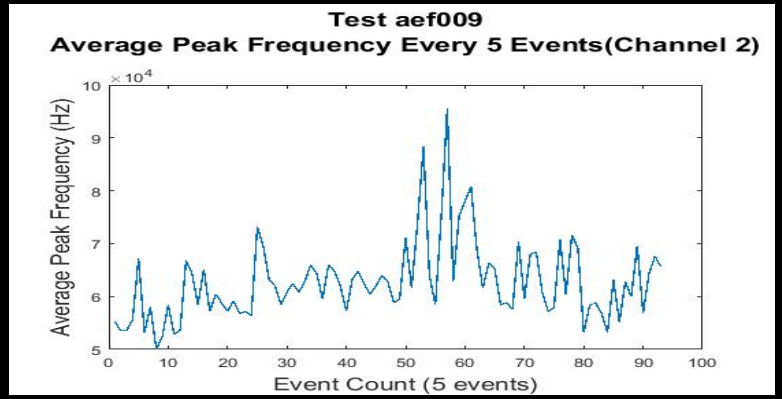
Results

Mean Acoustic Emission (Low Frequency)







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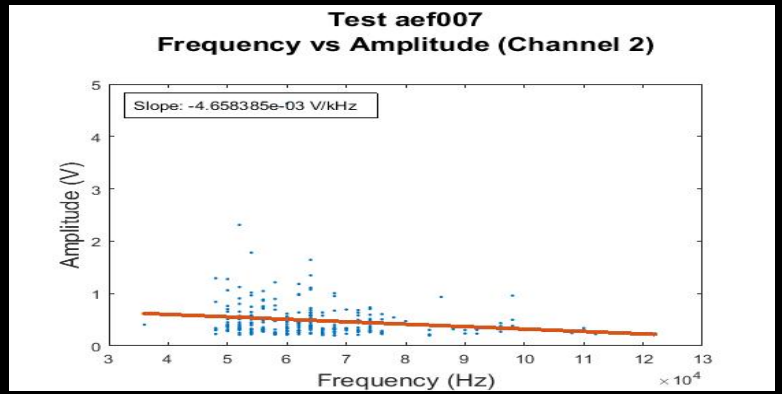
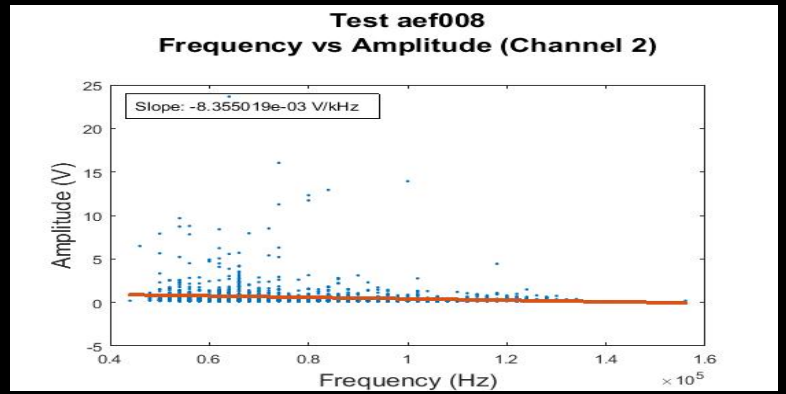
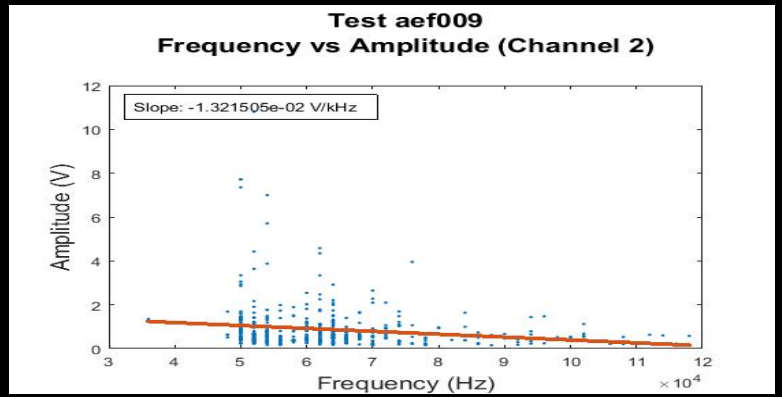
Results

Frequency vs Amplitude (Low Frequency)







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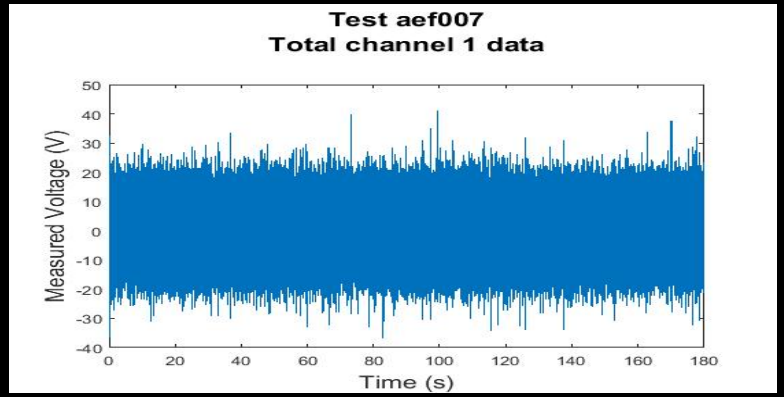
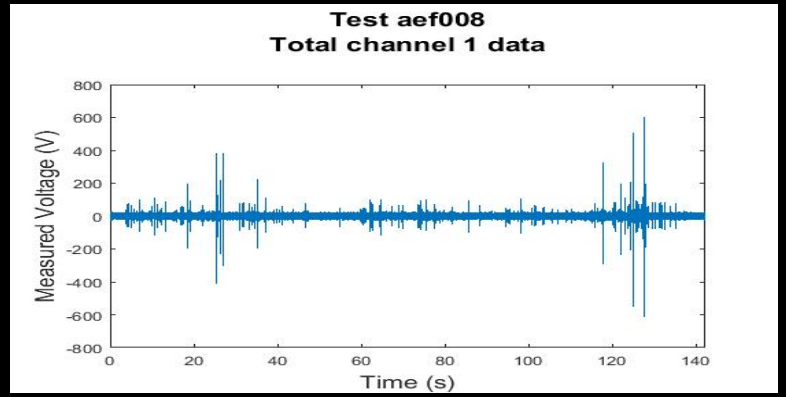
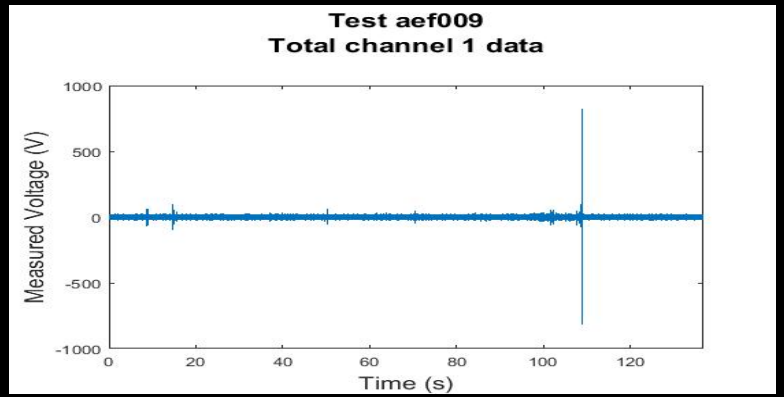
Results

Total measured signal (High Frequency)







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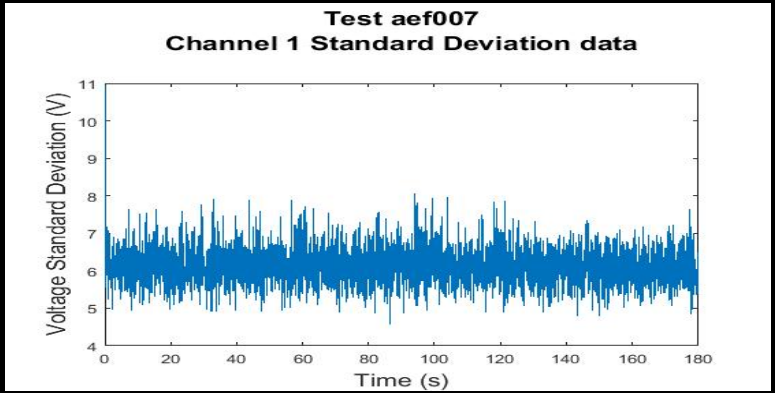
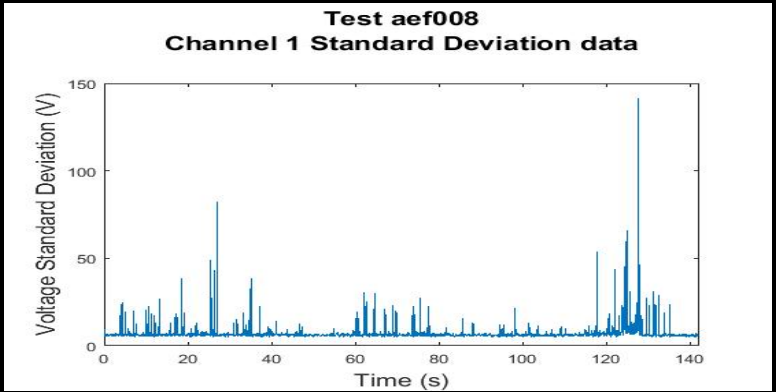
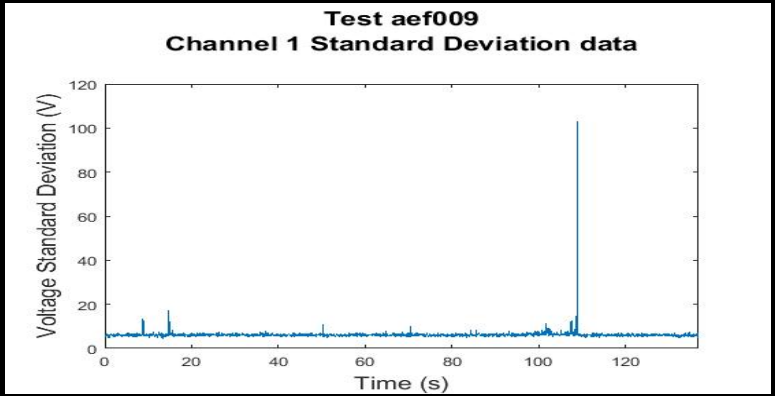
Results

Waveform Standard Deviations (High Frequency)







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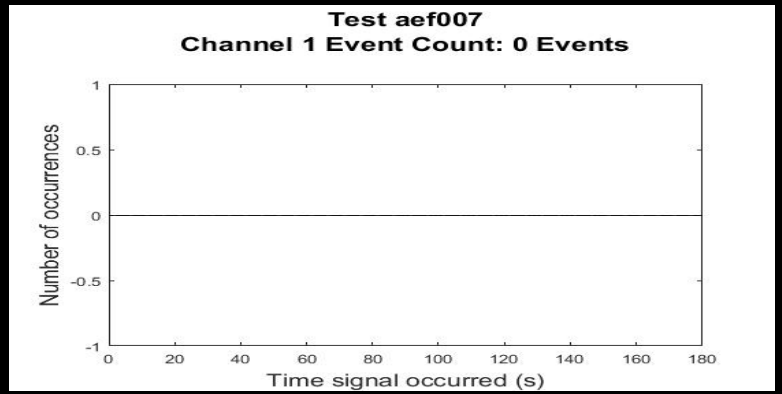
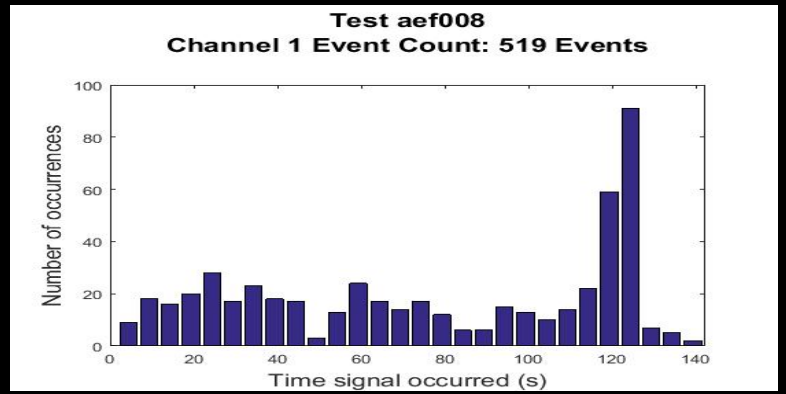
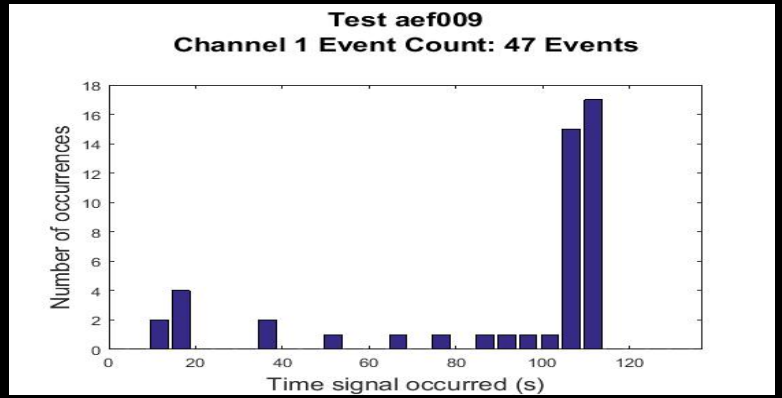
Results

Event Count Histogram (High Frequency)







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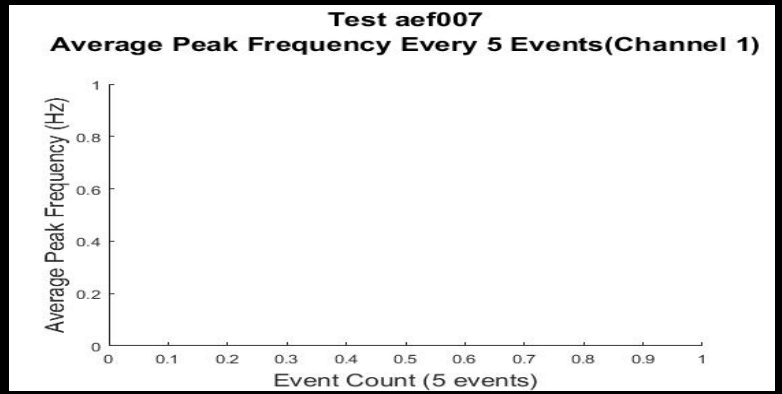
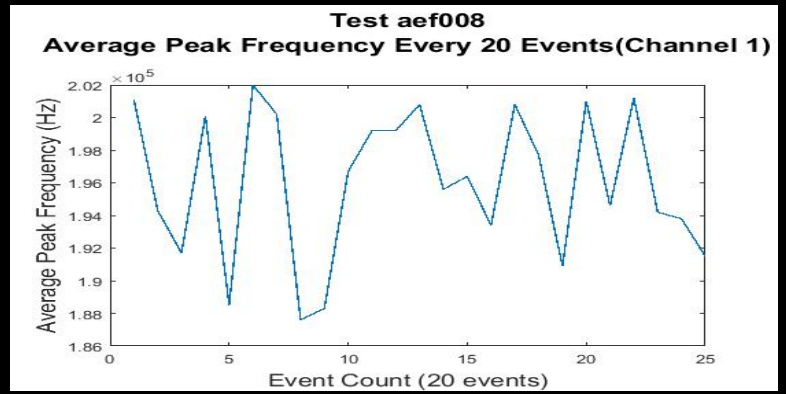
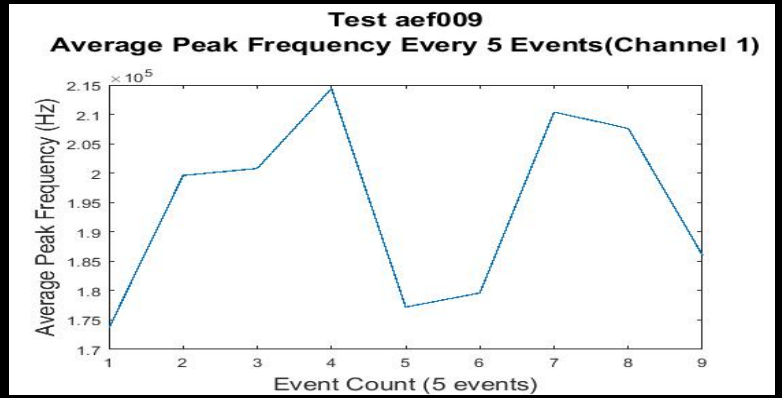
Results

Mean Acoustic Emission (High Frequency)



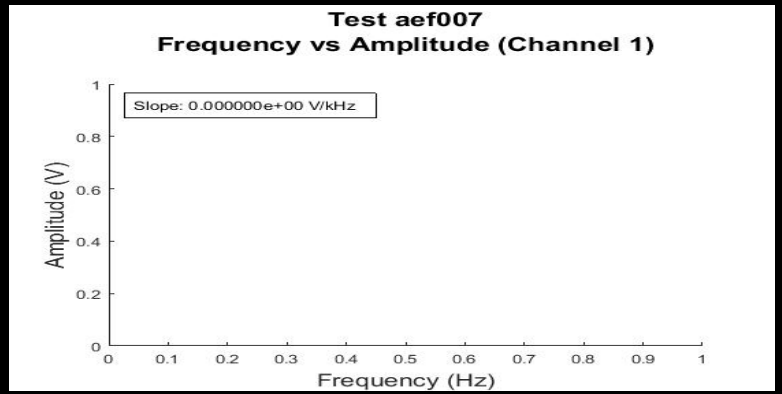


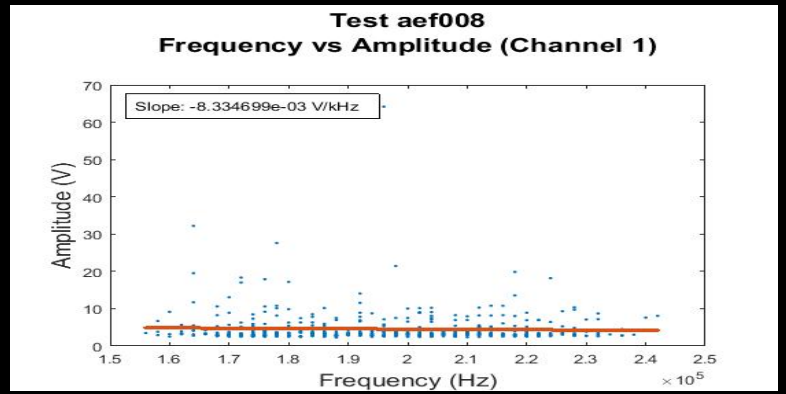


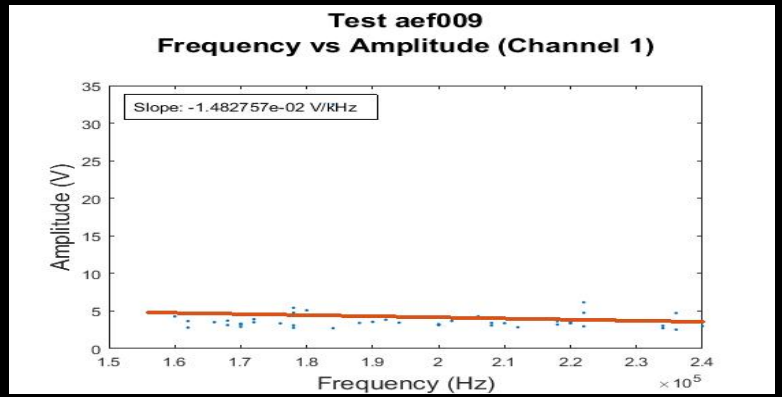
aef007 – Navajo Sandstone
aef008 – Basalt
aef009 – Grey Brown Sandstone

Results

Frequency vs Amplitude (High Frequency)



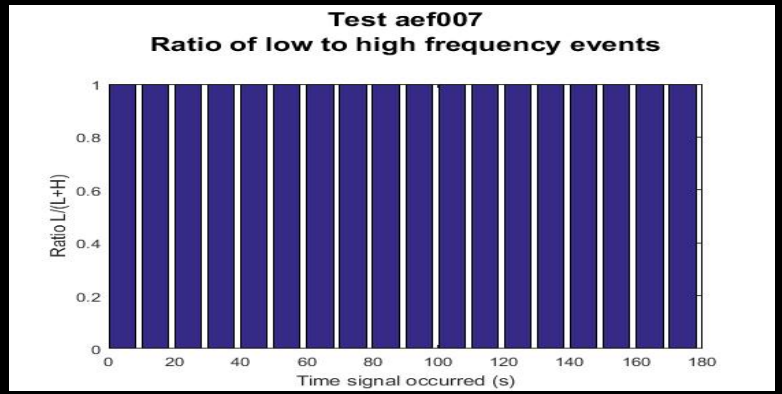


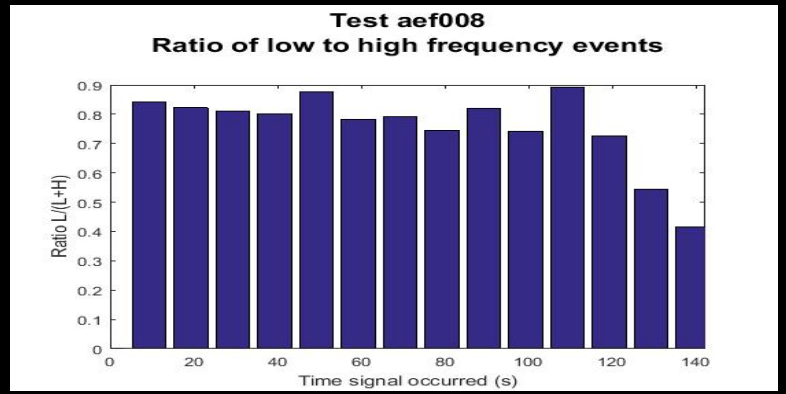


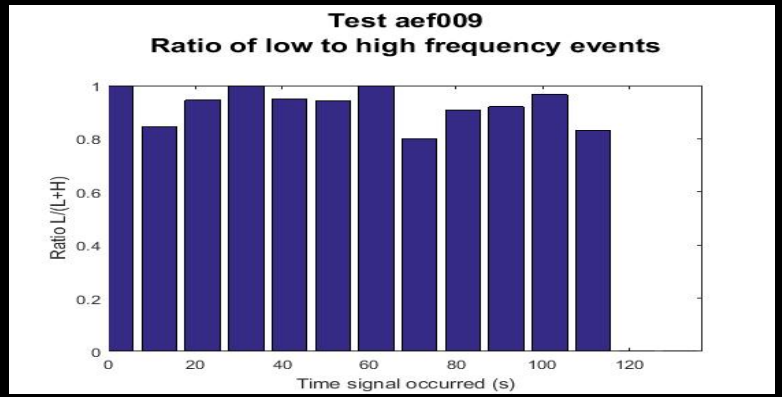
aef007 – Navajo Sandstone
aef008 – Basalt
aef009 – Grey Brown Sandstone

Results

Low to High Ratio Plots







aef007 – Navajo Sandstone
aef008 – Basalt
aef009 – Grey Brown Sandstone

Conclusions

Conclusive and Inconclusive Results

- Conclusive
  - Amplitude-frequency dependency was demonstrated.
  - Emission rate increases before failure.
- Inconclusive
  - Five-stage fracturing sequence based on $\frac{n(L)}{n(H)+n(L)}$
  - Change in frequency over time.

Experimental Limitations

- Imprecise stress and strain data.
- Noisy background.
- Transducers used were not built for contact acoustic emission detection.
- Poor sample rate
  - Time between samples is x120 greater than waveform timespan
- Inconsistencies in sample dimensions, strain rate, and coupling methods.

Future Experimental Method Improvements

- Store strain rate data
- Use cylindrical test samples for consistency
- Utilize PZT transducers developed for contact acoustic emission
  - Mistras Systems, Rao et al. (2011)
- Upgrade current preamp to one with a better SNR
- Replace oscilloscope with ultrasonic A/D convertor
- Develop a real time detection and processing algorithm

Future Research Questions

- Identify parameters that influence the occurrence of precursory emission sequences.
  - Strain rate, lithology, types of stress, sample geometry
- Quantify attenuation in fault-associated rocks.
- Discriminate between seismic and aseismic fault movement.
- Solve for the five qualities of an earthquake prediction.

Earthquake prediction

Qualifying a prediction

From Clarence R. Allen’s Presidential Address to the Seismological Society of America (1976):

1. It must specify a time window.
2. It must specify a space window.
3. It must specify a magnitude window.
4. It must indicate the author’s confidence in the reliability of the prediction.
5. It must be presented in some accessible form so that data on failures are as easily obtained as data on successes.

Image Credits

1. Green, Glenda. *Mossy Log Bridge*. [Photograph]. Retrieved from http://www.publicdomainpictures.net/view-image.php?image=24463
2. St. John, James. *Fault with fault breccia in interbedded metagraywacke-slate (Lake Vermilion Formation, Neoarchean, 2.695-2.722 Ga; Pike River Bridge outcrop, just north of Peyla, Minnesota, USA) 2.* [Photograph]. Retrieved from https://www.flickr.com/photos/47445767@N05/21622666821
3. Modified from Anders, M. H., Laubach, S. E., & Scholz, C. H. (2014). Microfractures: A review. Journal of Structural Geology, 69, p.378.
4. Mogi, K. (2007). Experimental rock mechanics (Vol. 3). CRC Press.
5. Lockner, D. (1993, December). The role of acoustic emission in the study of rock fracture. In International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts (Vol. 30, No. 7, p. 895). Pergamon.
6. Modified from Grosse, C. U., & Ohtsu, M. (Eds.). (2008). Acoustic emission testing. Springer Science & Business Media. P. 71.
7. Modified from Ohnaka, M., & Mogi, K. (1982). Frequency characteristics of acoustic emission in rocks under uniaxial compression and its relation to the fracturing process to failure. *Journal of Geophysical Research: Solid Earth*, *87*(B5), p.3876.
8. Modified from Ohnaka, M., & Mogi, K. (1982). Frequency characteristics of acoustic emission in rocks under uniaxial compression and its relation to the fracturing process to failure. *Journal of Geophysical Research: Solid Earth*, *87*(B5), p. 3878.
9. Gonsalvez, Richard J. *Gutenberg-Richter Plot.* [Graph]. Retrieved from http://www.physics.buffalo.edu/phy410-505/2011/topic1/app2/index.html
10. Modified from Ohnaka, M., & Mogi, K. (1982). Frequency characteristics of acoustic emission in rocks under uniaxial compression and its relation to the fracturing process to failure. *Journal of Geophysical Research: Solid Earth*, *87*(B5), p. 3877.
11. Modified from Ohnaka, M., & Mogi, K. (1982). Frequency characteristics of acoustic emission in rocks under uniaxial compression and its relation to the fracturing process to failure. *Journal of Geophysical Research: Solid Earth*, *87*(B5), p. 3877.
12. St. John, James. *Sierra Grande Andesite*. [Photograph]. Retrieved from https://commons.wikimedia.org/wiki/File:Sierra_Grande_Andesite.jpg
13. *Stone.* [Photograph]. Retrieved from https://pixabay.com/en/stone-granite-minerals-grey-rock-79106/.
14. Mogi, K. (2007). Experimental rock mechanics (Vol. 3). CRC Press. *p. XIII.*
15. Grosse, C. U., & Ohtsu, M. (Eds.). (2008). *Acoustic emission testing*. Springer Science & Business Media. P. 20.

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References Cited

Allen, C. R. (1976). Responsibilities in earthquake prediction: To the Seismological Society of America, delivered in Edmonton, Alberta, May 12, 1976. *Bulletin of the Seismological Society of America*, *66*(6), 2069-2074.

Cai, Dai-en, et al. "The b-value of acoustic emission during the complete process of rock fracture." *Acta Seismol. Sinica* 2 (1988): 129-134.

Lockner, D. (1993, December). The role of acoustic emission in the study of rock fracture. In *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* (Vol. 30, No. 7, pp. 883-899). Pergamon.

Mogi, K. (1962). Study of elastic shocks caused by the fracture of heterogeneous materials and its relations to earthquake phenomena.

Ohnaka, M., & Mogi, K. (1981). Frequency dependence of acoustic emission activity in rocks under incremental, uniaxial compression.

Ohnaka, M., & Mogi, K. (1982). Frequency characteristics of acoustic emission in rocks under uniaxial compression and its relation to the fracturing process to failure. *Journal of Geophysical Research: Solid Earth*, *87*(B5), 3873-3884.

Rao, M. V. M. S., Lakshmi, K. P., Rao, G. N., Vijayakumar, R., & Udayakumar, S. (2011). Precursory microcracking and brittle failure of Latur basalt and migmatite gneiss under compressive loading. *Current Science(Bangalore)*, *101*(8), 1053-1059.

Scholz, C. H. (1968). The frequency-magnitude relation of microfracturing in rock and its relation to earthquakes. *Bulletin of the Seismological Society of America*, *58*(1), 399-415.

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