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Supporting Information for "Normalised Radiated Seismic Energy from Laboratory Fracture Experiments on Opalinus Clayshale and Barre Granite"

Bing Q. Li[1,2], Herbert H. Einstein[2]

[1]Division of Geological and Planetary Sciences, California Institute of Technology

[2]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology

Amplitude attenuation is a concern for the estimation of radiated seismic energy from shale materials, as it has been shown in this and other works (e.g. Moradian et al. (2015)) that the quality factor, which is inversely proportional to amplitude attenuation, is significantly lower in shale than other rocks. While the ball drop magnitude calibration method implicitly accounts for attenuation, we nevertheless use the coda-decay method (Aki & Chouet, 1975) to explicitly estimate the quality factor Q from the waveforms acquired from the 0.019 mL/s hydraulic fracturing Opalinus experiment, in order to quantify the difference between granite and shale attenuation. Note that this analysis was only conducted on one test per material, as we do not expect the attenuation factor to vary dramatically between samples. The Q at a given frequency can be expressed as:

Corresponding author: B.Q. Li, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA, 91125. (bingqli@caltech.edu)

$$ln(A_c(f,t_c) \cdot t_c) = ln(I(f)A_0(f)) - \frac{\pi f}{Q_c}t_c \tag{1}$$

Where $A_c(f,t_c)$ is the amplitude in a given frequency band f and time after event origin time t_c, Q_c is the quality factor, and $ln(I(f)A_0(f))$ is a constant. If we plot $ln(A_c(f,t_c)t_c)$ vs. t_c, the slope is then equivalent to $-\frac{\pi f}{Q_c}$.

We first select a small (Figure S1a) and a large (Figure S2a) waveform, and filter by frequency bands 25 - 50 kHz, 50 - 100 kHz, 100 - 200 kHz, and 200 - 400 kHz using a 2-pole Butterworth filter, as shown in Figures S1 and S2. From these filtered plots, we select a window size of 20 μs by inspection, over which to calculate the moving average RMS for each frequency band, as shown in Figures S1f and S2f.

The moving average is calculated for every waveform acquired during the test, normalised by the corresponding first arrival amplitude, and presented on the same plot for each channel. As an example, the plot of channel 5 is shown in Figure S3. The slope, as denoted by the dotted red line, is approximated by visual inspection immediately after the maximum y-axis value, and is equivalent to $-\frac{\pi f}{Q_c}$. The calculated Q values are summarised in Table S1.

The calculated Q values are similar to those found in other lab studies on shale (Hu et al., 2018; Zhai et al., 2017; Dend et al., 2009). We can then use equation 2 (Stokes, 1845) to estimate the amplitude attenuation for our laboratory setting.

$$Attenuation\ factor = e^{\frac{-2\pi f x}{2cQ}} \tag{2}$$

Where we assume x, the distance from the source, to be 25.4 mm (the distance from the notch to the side of the specimen); c, the wave velocity, to be 3000 m/s from in-situ measurements. We consider the 100-200 kHz frequency band as the dominant frequency lies in this range, at which the mean quality factor is Q = 8.4. The attenuation factor, then, is 0.63, i.e. the amplitude detected at the sensor is 63 % of the amplitude if the sensor was immediately at the source. This number is quite high, and so we can generally conclude that the effect of attenuation is not significant, thus not many events were undetected due to attenuation effects.

Similar analyses were conducted on the 0.019 mL/s granite HF experiment, and the results are shown in Figure S4 and Table S2. We can see that the quality factor for granite is generally twice that of shale, which results is slightly less attenuation. The mean quality factor of Q = 16.81 in the 100-200 kHz band resolves to an attenuation factor of 84 %. However, this difference in quality factor of 8.4 for the shale and 16.8 for the granite does not explain the 100x difference in radiated seismic energy between granite and shale calculated in this study.

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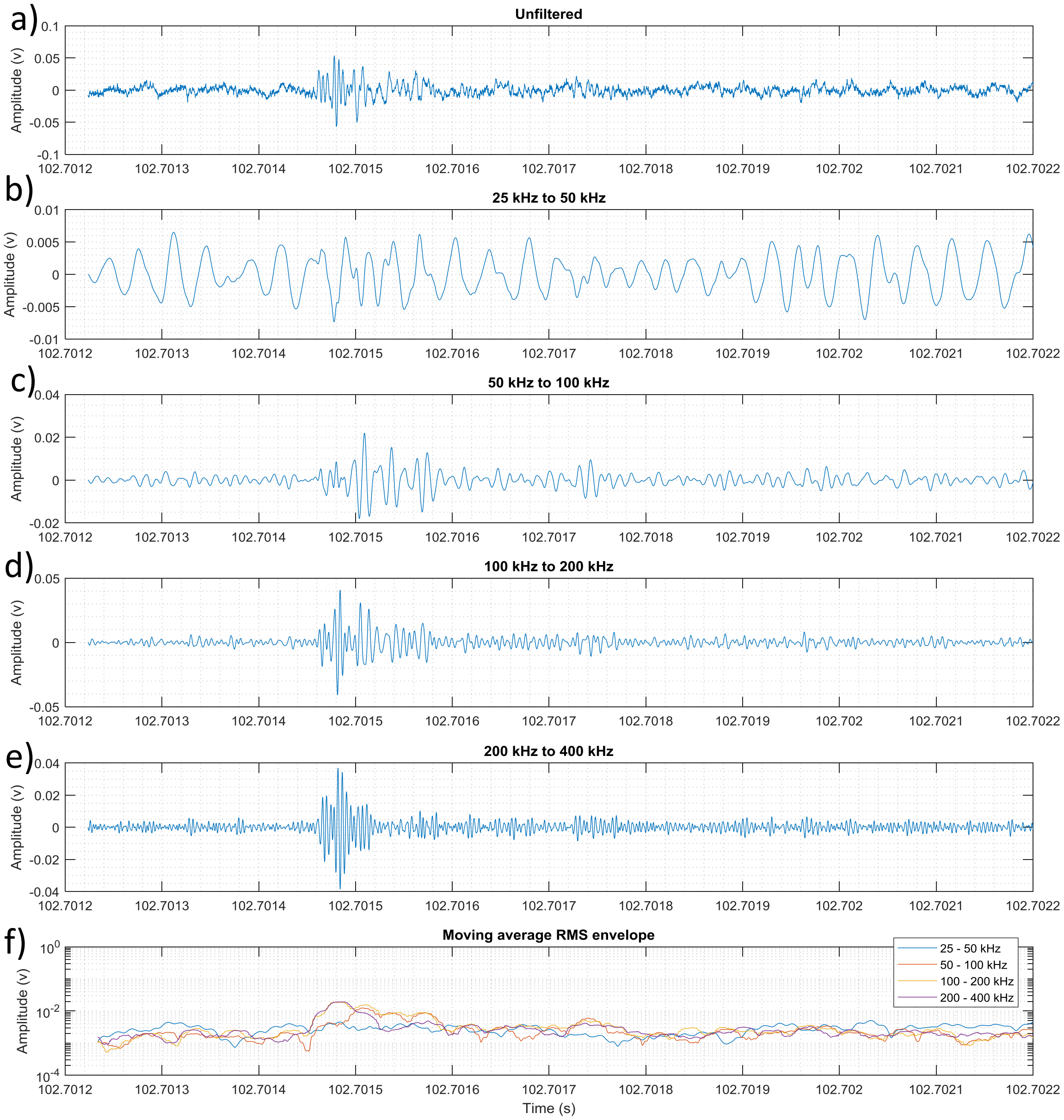

Figure S1. a) Unfiltered small amplitude waveform from 0.019 mL/s Opalinus test. b) - e) Waveform filtered at indicated frequency bands. f) Moving average RMS envelope of each frequency filtered wave.

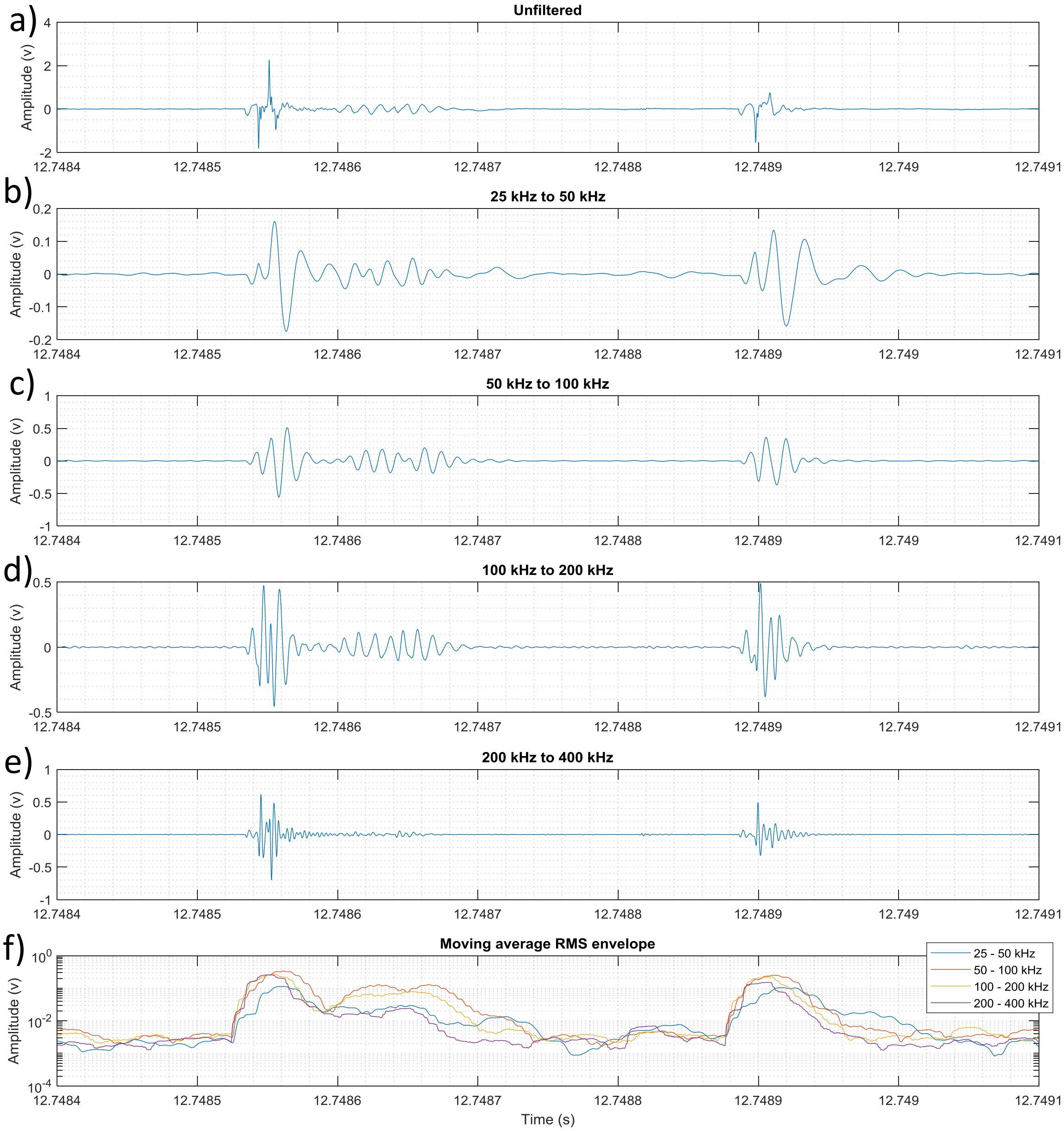

Figure S2. Same as Figure S1, but for a large amplitude waveform.

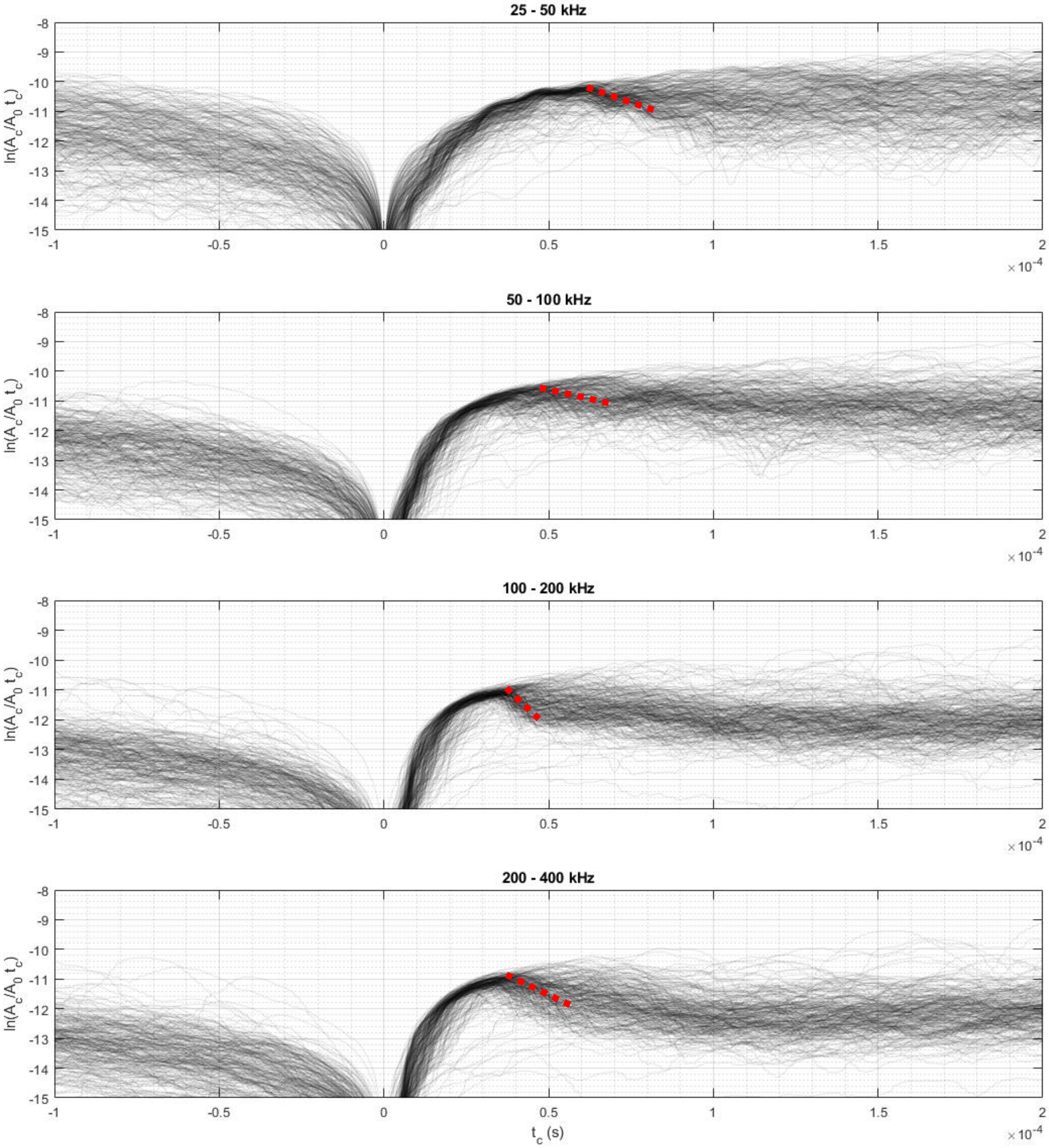

Figure S3. Waveform envelopes for all events detected at channel 5 during 0.019 mL/s HF Opalinus clayshale experiment, presented for each frequency band. Dotted red line shows slope estimating $-\frac{\pi f}{Q_c}$.

Table S1. Summary of calculated Q for Opalinus clayshale per channel, per frequency band based on 0.019 mL/s HF experiment. Note that Q was not calculated for some channels and frequency bands, as no clear slope could be picked from the waveform envelopes.

Q_P	Frequency (kHz)			
Channel	25 - 50	50 - 100	100 - 200	200 - 400
1		4.45	15.13	7.87
2		5.48	5.16	11.75
3		5.62	9.13	24.16
4		10.44	5.76	17.67
5	3.50	7.11	4.25	18.54
6				
7				
8		0.40	11.01	32.52
Average	3.50	5.58	8.41	18.75

Table S2. Summary of calculated Q for granite per channel, per frequency band based on 0.019 mL/s HF experiment. Note that Q was not calculated for some channels and frequency bands, as no clear slope could be picked from the waveform envelopes.

Q_P	Frequency (kHz)			
Channel	25 - 50	50 - 100	100 - 200	200 - 400
1	6.40	5.63	26.38	55.80
2				
3	14.35	13.01	21.84	23.82
4	6.34	12.40	16.23	34.63
5	4.52	35.67	4.62	17.92
6	18.72	7.85	16.66	67.02
7				
8	6.75	13.62	15.14	31.14
Average	9.51	14.70	16.81	38.39

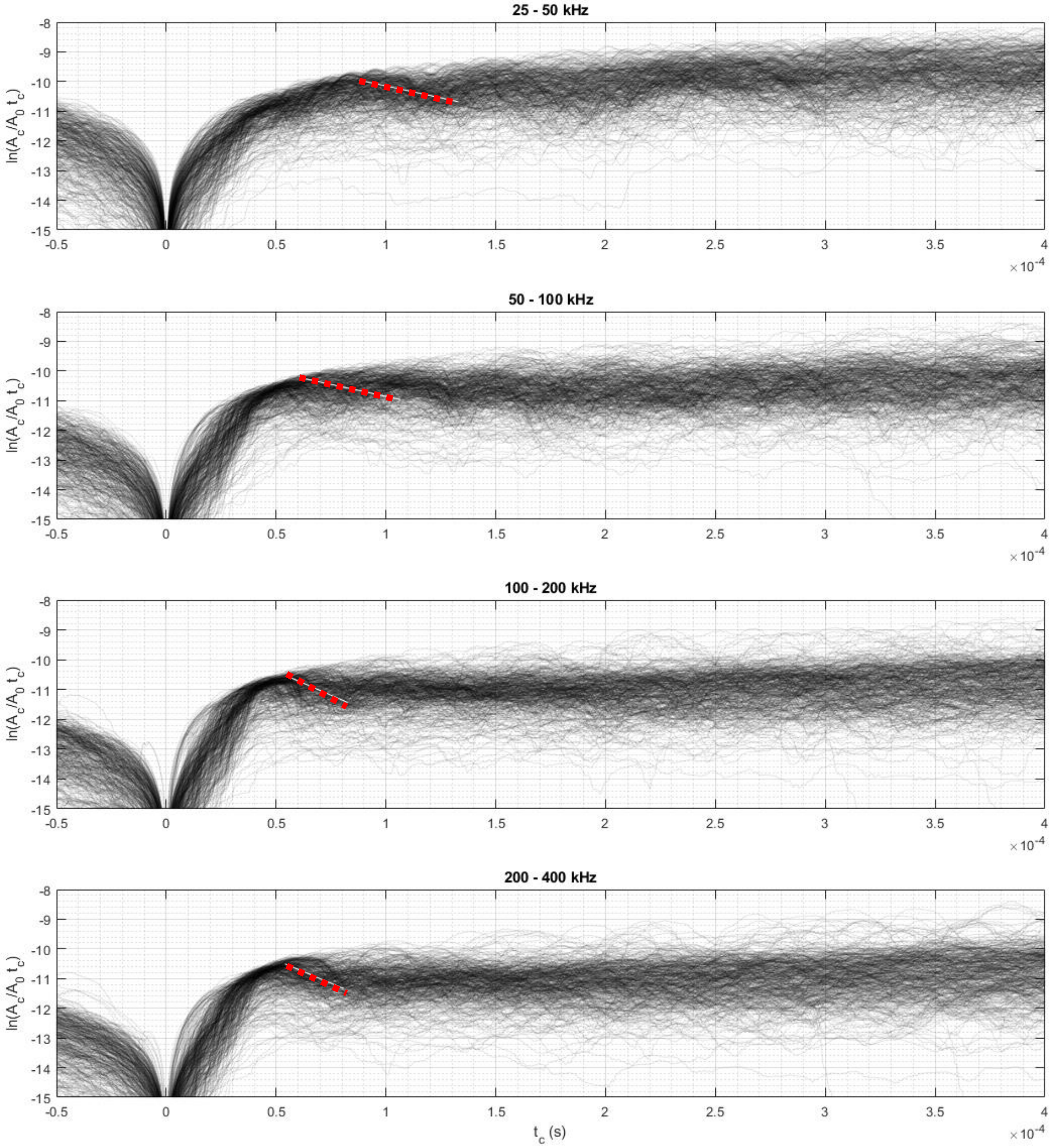

Figure S4. Same as Figure S3, but for granite