Magnitude Assessment and Effective Interpretation of Microseismicity

Adam Baig* and Ted Urbancic
Engineering Seismology Group, Kingston, ON, Canada
adam.baig@esg.ca

Introduction

Magnitudes and locations are the first-order output for microseismic events recorded during hydraulic fracture stimulations and longer term reservoir based extraction operations (eg., CSS, SAG-D, CO_2 sequestration). The magnitude describes the strength of an event and tells us about the dynamics of the fracturing processes and the distribution of magnitudes outlines the effectiveness of the data acquisition configuration. A number of different magnitude scales have been proposed over the years: most are lacking in that they do not relate magnitude to a physical model. The exception is moment magnitude, introduced by Hanks and Kanamori (1979), which can be used to bridge waveform amplitudes to the fault area and slip though seismic moment, assuming the recording system is tuned to the appropriate signal bandwidth. We will describe the moment magnitude calculation, the role of proper instrumentation in determining the quantity, and discuss how magnitude is used to obtain an unbiased assessment of the effectiveness of an injection program.

Theory

A number of magnitude scales exist in the literature. Some are tailored to a particular region with slightly different calibration curves and others suited for different seismic phases. In general, these relationships can be summarized as:

$$Magnitude = log_{10}\,(Amplitude) + CorrectionFactor$$

where the correction factor depends on distance and sometimes the period of the waveform. However, such scales are unabashedly empirical and there is no tie to a physical model so a given magnitude cannot be explicitly related to any parameters of the fracture. Hanks and Kanamori (1979) developed the moment magnitude scale to relate the waveforms with a parameter of the fracturing process, the seismic moment M_0,

$$M_0 = \frac{4\pi\rho c^3 |W_c| R}{F_c}$$

where $|W_c|$ is the low-frequency plateau of the displacement spectrum (see figure 1), R is the geometrical spreading, c is the wave-speed, ρ is the density of the rock (at the source), and F_c represents the radiation pattern imposed by the moment tensor. With seismic moment, measured in Nm, we can then determine moment magnitude from the following formula:

$$M_W = \frac{2}{3}\log_{10} M_0 - 6.$$

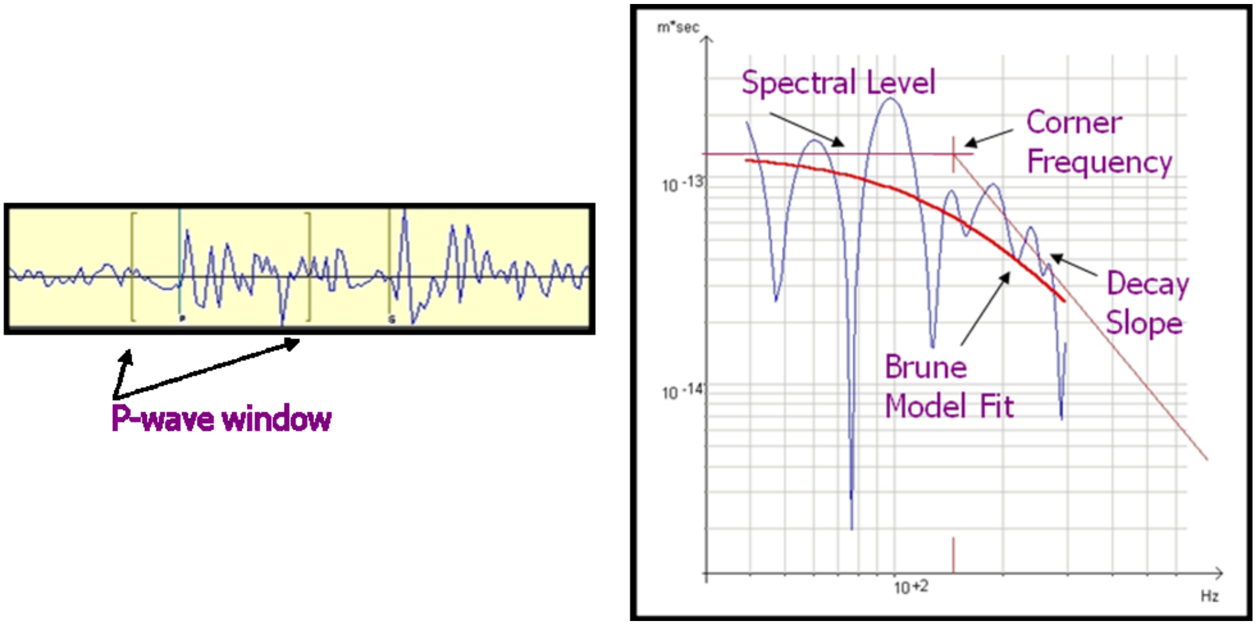

Figure 1. A P waveform and its displacement spectrum based on the shown P-wave window. The magnitude is calculated assuming the Brune model to determine the spectral level and corner frequency. The decay slope represents a fit to a -2 theoretical slope as corrected for attenuation.

Instrumentation

Because of the band-limited nature of seismic signals, the design of the recording system is an important consideration in any discussion of magnitude. The corner frequencies (see figure 1) for microseismic events, in the magnitude range of -3 to 0, range from ~ 50 to 500 Hz. To accurately assess the shape of the spectrum the recording system has to faithfully record to at least twice the corner frequency. Therefore, to accurately calculate magnitude, the bandwidth of the instrument needs a sampling rate of a minimum of four times the largest frequency, or ~4000 Hz.

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Application

The moment magnitude controls the range of detectability of microseismic events and is, therefore, a very important consideration in determining how a treatment should be monitored. Figure 2 shows the magnitude versus distance plot for a hydraulic fracture in a shale formation. The minimum detectable magnitude (solid line) appears to increase with distance. For data completeness, as represented by the dashed horizontal line, there is an equal probability of detecting an event of M > -1.4 over the entire volume of interest. The distribution also suggests events were only detectable to a distance of approximately 1600 ft from the observation array. In this case, unbiased interpretation can only be provided by considering the complete data set.

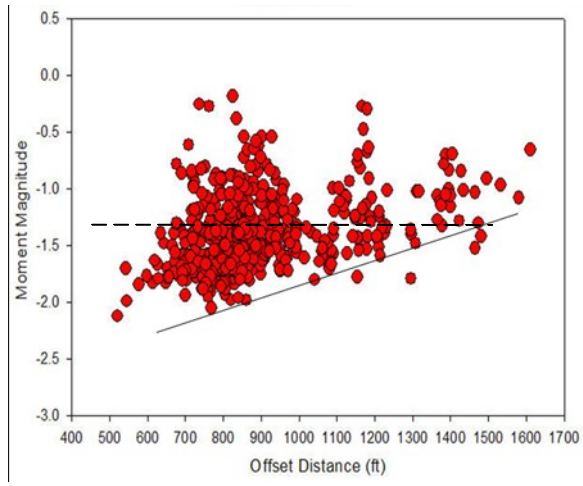

Figure 2. Magnitude-distance plots for a hydraulic fracture in a shale formation. As shown, there is no recording bias for M > -1.4 and there is an equal probability of observing an event with M > -1.4 throughout the volume of interest.

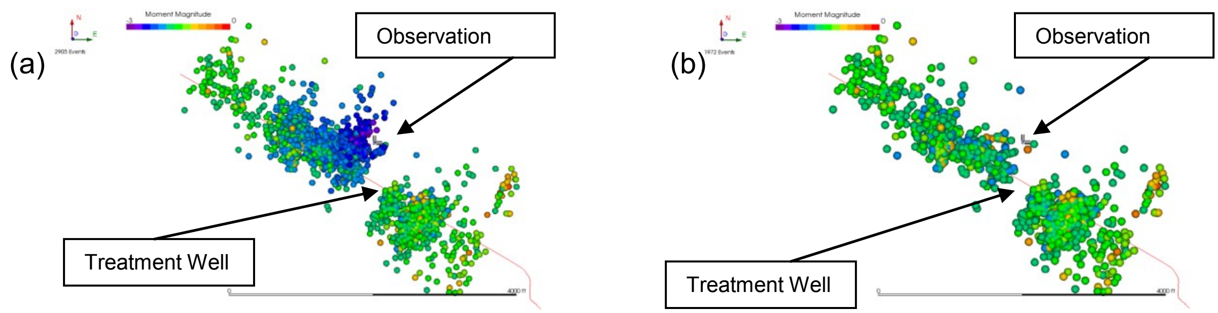

Figure 3. (a) All events from a hydraulic fracture colour scaled by moment magnitude and (b) the same hydraulic fracture with a complete event catalogue leading to a more representative identification of fracture dimension (eg., lengths) and fracture symmetry, and stimulation effectiveness (fracture volumes possibly related to production).

To build on the point of obtaining an unbiased estimate of fracture geometry, we discuss the distribution of all events recorded from a hydraulic fracture in shales, shown in Figure 3a. There is apparent growth out from the horizontal treatment well beyond the observation well. By considering only those events representing the minimum magnitude that can be observed across the entire dataset we can define a complete data set for the volume. By excluding events below this threshold, we homogenize the data and we see that, in Figure 3b, the low-magnitude tongue of events beyond the observation well has disappeared. So we can conclude the stages comprising these low-magnitude events are not exceptional compared to the further stages which were too far out for similar low-magnitude events to be registered.

Conclusions

Of all magnitude scales, moment magnitude uniquely speaks to the physics of the fracture though the seismic moment, and for this reason, should be considered above all the other magnitudes in the microseismic regime. For microseismicity, the bandwidth of the instruments needs to capture corner frequencies in the range of 100 to 500 Hz, consequently sampling rates need to be at least 4000 Hz to accurately calculate the moment magnitude, and as observed, magnitude is relevant for interpreting the effectiveness of the injection program and unbiased interpretation.

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