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The Application of the Signal Duration Method for Magnitude Estimation of Microseismic Events

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Summary

A trilinear scale was developed for magnitude estimation of seismic events within a magnitude range of $-3 < M < 4$ based on the signal duration (or coda length) of the seismic event. This scale was obtained from a near-surface microseismic monitoring dataset of a hydraulic fracturing stimulation in a shale-gas reservoir in the Duvernay Formation, in western Canada, where 17 seismic events of magnitudes between 1.5 and 3.6 were induced during the stimulation and reported by a regional seismological network. The reported magnitudes of these events were implemented to calibrate an energy-based magnitude scale, and to estimate the magnitudes of the microseismic events detected during the monitored stimulation. The proposed trilinear scale was obtained from a regression between the estimated energy magnitudes and the measured coda lengths for the same events, and can be implemented in future hydraulic-fracturing monitoring projects to estimate the magnitude of detected microseismic events.

Introduction

The magnitude of an earthquake is a measure of its physical size and can predict the ground motion and potential damage that it could cause (Havskov and Ottemöller, 2010). The original local magnitude scale M_L defined by Charles Richter for southern California in 1935 is based on a logarithmic scale of the maximum amplitude in a ground displacement record measured on a Wood-Anderson seismogram (Richter, 1935). Although modern digital instruments have evolved from the original Wood-Anderson design, the local magnitude method is still preferred to report the magnitude of regional earthquakes. However, multiple sources of error can be encountered with a magnitude estimation based on maximum amplitudes. Amplitudes change rapidly with distance due to attenuation, a factor often ignored in surface seismic processing (Shemeta and Anderson, 2010). Amplitude saturation (or clipping) can also occur for high magnitude seismic events or for events recorded with seismic stations located very close to the hypocenter. Magnitudes calculated using a local magnitude scale are problematic in these cases.

A more rigorous method for magnitude estimation is the moment magnitude scale (M_w) proposed by Hanks and Kanamori (1979). This scale is based on the definition of seismic moment M_0 that can be calculated from the corner frequency f_0 and the spectral flat level Ω_0 obtained from the source displacement spectrum proposed by Brune (1970). The sensor sensitivity and bandwidth play a key role in the estimation of f_0 and Ω_0 , and therefore in the calculation of the seismic moment. A short-period sensor (e.g. a 10 Hz geophone), such as those typically used in conventional seismic exploration, cannot record accurately the seismic signal below its natural frequency and will generate erroneous calculations of both f_0 and Ω_0 . The corner frequency of the source spectrum of a seismic event decreases as the magnitude increases, where f_0 below 10 Hz are typical for seismic events of magnitude above 2 (Shearer, 2009). Different moment magnitude scales and instrument calibration parameters (or the lack of instrument calibration in many cases) can also lead to erroneous calculations of M_w , (see for example Shemeta & Anderson, 2010). For low magnitude events (such as those typically reported for hydraulic fracturing stimulations), the corner frequency is higher than the natural frequency of short period sensors (e.g. f_0 of approximately 200 Hz for a seismic event of magnitude 0), but can also be higher than the Nyquist frequency (f_N) of the recorded data (which is half of the sampling frequency), and therefore can also leads to erroneous calculations of M_w .

To address this magnitude uncertainty, a signal duration method -also called coda magnitude method- is proposed to estimate the magnitude of microseismic events. The signal duration, which is a measurement of the duration of coda waves after the arrival of P and S waves to a seismic station, has been reported to be remarkably constant with distance (unlike amplitudes which change rapidly with distance), making this parameter a very stable method to calculate magnitudes (Lee et.al., 1972). The signal duration can also be reliably measured on different seismic stations (unlike maximum amplitudes or frequency-spectrum parameters required for local magnitude or moment magnitude estimations), making it very convenient for magnitude estimations of microseismic events typically monitored with short-period sensors. The radiated seismic energy can also be implemented to estimate the magnitude of a seismic event from an empirical relation (Bormann, 2002). The cumulative squared waveforms recorded from short-period geophones or broadband seismometers, both of them designed to measure ground velocities, are directly related to kinetic energy (Atkinson and Kaka, 2007) and can be implemented to calibrate a magnitude scale.

These two methods are applied in a case study of an unconventional shale-gas reservoir in the Duvernay formation located in the Fox Creek region in central Alberta, Canada. A well with four horizontal tracks was drilled in a north-south direction, and a multi-stage hydraulic fracturing stimulation was performed. Due to the observed recurrence in recent years of high-magnitude seismic events associated with hydraulic fracturing operations in this region (Schultz et.al., 2017), it is mandatory to conduct seismic monitoring during any completion operations including hydraulic fracturing (Alberta Energy Regulator, 2015). This stimulation was monitored by a borehole seismic array equipped with 3C 10 Hz geophones buried 27 meters and with a sampling frequency of 500 Hz (therefore, $f_N=250$ Hz). Some seismic events with magnitude higher than 1.5 were also detected and reported by a regional seismological network. The reported magnitudes of these events were used to calibrate the radiated energy and the energy and coda magnitude scales for this case study. One seismic event with signal-to-noise ratio (S/N) was used as a template event to detect automatically microseismic events based on a cross-correlation function (around 6000 events were detected), and to pick the P- and S-wave arrivals of all the detected events.

The Signal-Duration Magnitude Method

The signal duration –or Coda- magnitude method (M_c), is the simplest method to estimate the magnitude of a local earthquake (Havskov and Ottemöller, 2010). This method consists on a linear relation between the signal duration with the magnitude as defined by the following logarithmic scale:

$$M_c = \mathbf{a} \text{Log}_{10}(t_{coda}) + \mathbf{b} r + \mathbf{c}, \quad (1)$$

where M_c is the coda magnitude, t_{coda} is the signal duration (or coda time), r is the distance between the hypocenter and the seismic station in km, and \mathbf{a} , \mathbf{b} and \mathbf{c} are scale parameters that must be calibrated for each seismological network. The definition of t_{coda} is the duration between the P-phase arrival and the end of the S-wave signal where the noise level after the S phase arrivals matches the noise level before the P-phase arrival. Therefore, this definition requires the picking of both P and S-phase arrivals.

During the monitored hydraulic fracturing stimulation, 17 seismic events of magnitudes between 1.5 and 3.6 were reported by a regional seismological network in western Canada. The earthquake catalog from this network reports hypocentres' locations with uncertainties of a few kilometers, and the magnitude in local or moment magnitude scales (ML or MW). The link between large-magnitude seismic events induced by hydraulic fracturing operations has been very well documented for the Duvernay Formation, especially in the Fox Creek area where this case study is located (see for example Schultz, et al. 2017). These large-magnitude events were detected by the borehole 3C monitoring array, and the P and S-phase arrivals were manually picked in the vertical and horizontal components respectively to improve the hypocenter locations. The coda time was automatically picked for each station by matching the noise level before the P-wave arrival and after the S-wave arrival, in the logarithmic-scale amplitude of the horizontal components of each Borehole 3C station (Figure 1).

The seismic energy of the same events was measured by implementing the 2(Ts-Tp) algorithm proposed by Cuéllar et.al. (2017) (see Figure 2), and calibrated from their reported magnitudes to estimate

the magnitudes of the detected microseismic events. A linear regression was implemented between the calculated magnitudes from the calibrated seismic energy and the average of the measured t_{coda} of the same events in the Borehole 3C array, obtaining the following trilinear Coda-Magnitude scale for the monitoring array (see Figure 3):

$$M = \begin{cases} 3.0366 \text{ Log}_{10}(t_{coda}) - 3.2139, & t_{coda} \geq 30s \\ 1.316 \text{ Log}_{10}(t_{coda}) - 0.6331, & 30s > t_{coda} > 7s. \\ 3.7598 \text{ Log}_{10}(t_{coda}) - 2.5881, & t_{coda} \leq 7s \end{cases} \quad (2)$$

As shown in Figure 3, the obtained trilinear scale is similar to other coda magnitude scales reported for other regions of the world (summarized in Table 6.5 from Havskov & Ottemöller (2010)) for magnitudes higher than 1.5, including the bilinear scale proposed by Bakun & Lindh (1977) for California where a sharp change on the linear scale was observed for $t_{coda} < 30$ seconds. Similar than the proposed trilinear scale, none of these magnitude scales report a significant correction for distance (which corresponds to the parameter b from Equation 1 and Table 6.5 from Havskov & Ottemöller (2010)).

Conclusions

The obtained trilinear scale for magnitude estimation of microseismic events from their coda lengths was based on an energy-based magnitude scale calibrated from the magnitudes of strong seismic events ($1.5 < M < 3.6$) reported by a regional seismological network in western Canada. This scale is similar to other coda-magnitude scales reported for other regions of the world for magnitudes higher than 1.5, and can be implemented in future hydraulic-fracturing monitoring projects to estimate the magnitude of detected microseismic events.

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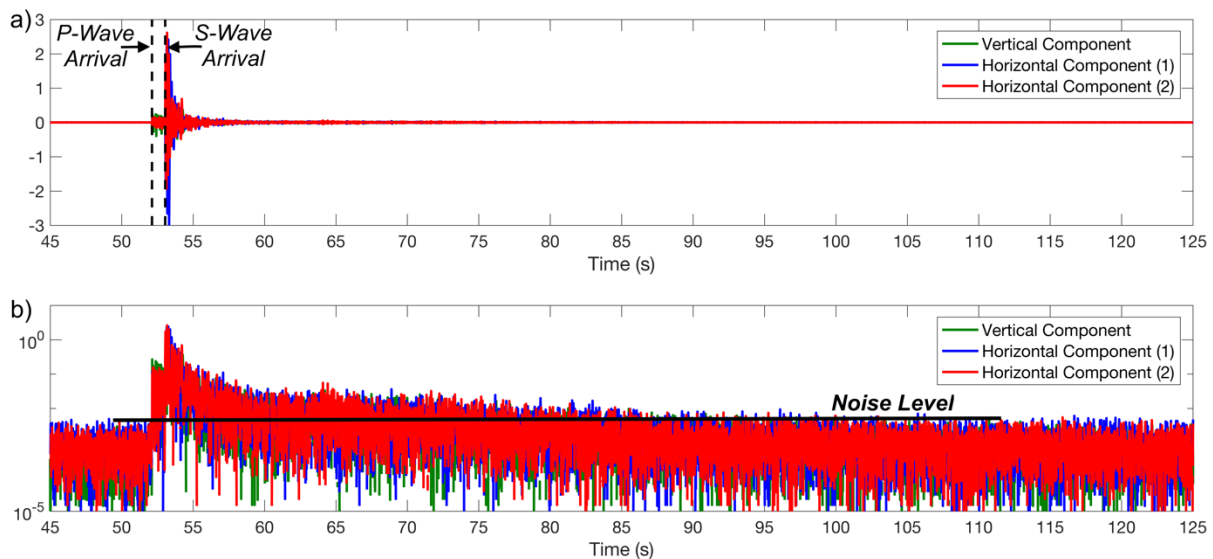


Figure 1. Automatic picking of the signal duration of a M_L 2.8 seismic event reported by a regional seismological network, and detected in the borehole 3C monitoring array. a) Seismic waveforms recorded at one station from the borehole 3C monitoring array, with the picking of P and S-phase arrivals. b) Logarithmic scale of the amplitudes of the seismic waveforms shown in a) with the noise level implemented to pick the coda time.

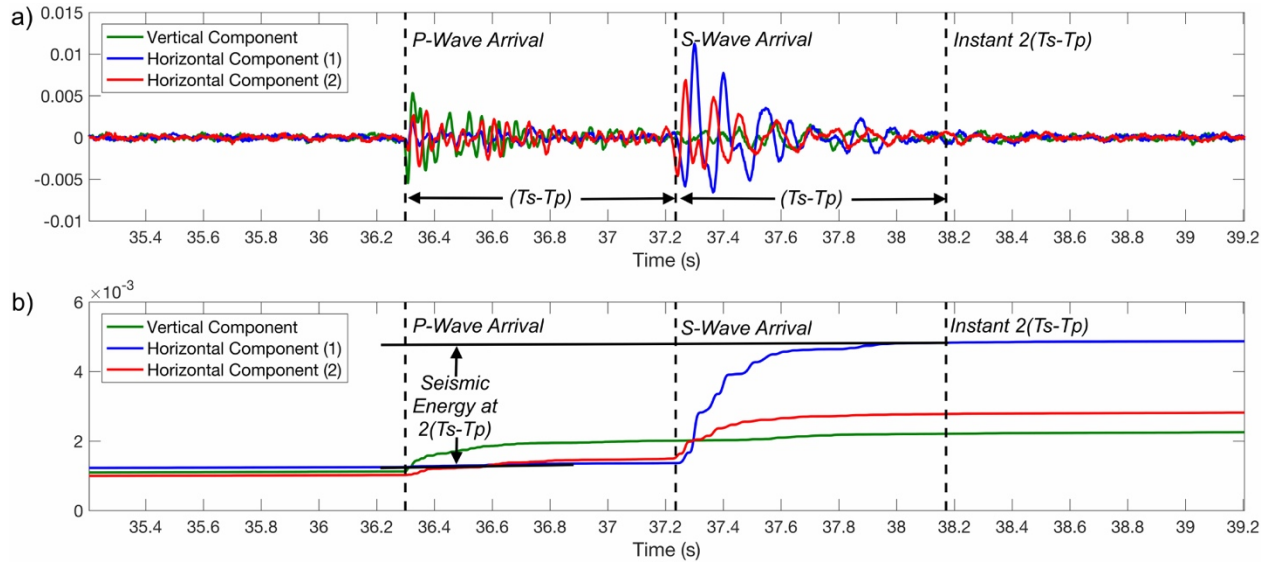


Figure 2. a) Seismic waveforms of a microseismic event recorded with one borehole 3C monitoring station, with picked P- and S-wave arrivals and the calculated time for the instant $2(Ts-Tp)$. b) Cumulative squared amplitude of the seismic traces shown in a). The seismic energy at $2(Ts-Tp)$ of the microseismic event corresponds to the difference between the cumulative squared amplitude at the instant $2(Ts-Tp)$, and at the P-Wave arrival time measured on the horizontal components of the seismic records.

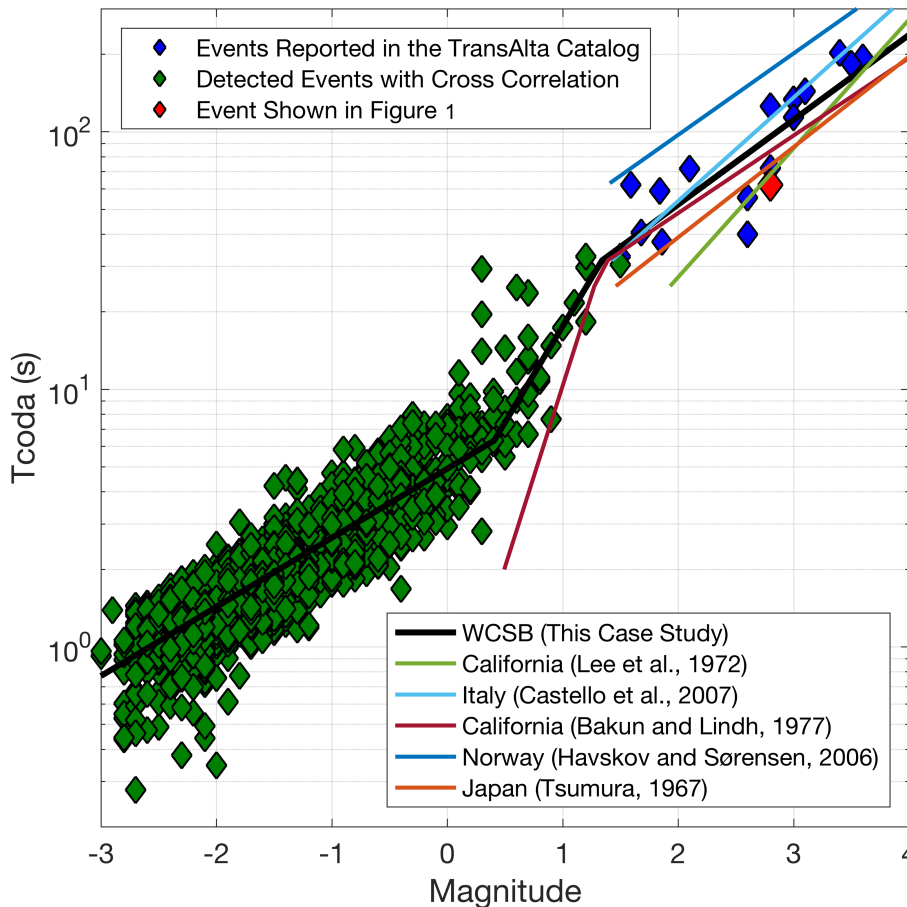


Figure 3. Trilinear relation between the coda length and magnitudes (Equation 2) calculated from the calibrated radiated energy (obtained from the $2(Ts-Tp)$ method described in Figure 2) of the detected seismic events obtained for this case study located in the western Canada sedimentary basin (WCSB), and compared with other coda magnitude scales reported for other regions of the world.

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