



## A Local Magnitude ( $M_L$ ) Formula for Western Alberta

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### Summary

We examine the distance attenuation of peak Wood-Anderson (WA) amplitudes obtained from earthquakes in western Alberta, to develop a regionally-calibrated local magnitude ( $M_L$ ) equation. A comparison of WA amplitudes from earthquakes and mining/quarry blasts in the region show that both event types decay at similar rates with distance and demonstrate a considerable Moho-bounce effect between 100 km and 220 km. Motivated by this observation, we merge the two amplitude datasets, and model the regional attenuation using a trilinear model to account for the observed shape of attenuation. We also determine a site correction for each station, which enables determination of  $M_L$  for a reference site condition. The derived  $M_L$  equation results in unbiased magnitude estimates with distance in western Alberta, and attains systematically lower values than the existing magnitudes computed based on standard  $M_L$  models.

### Introduction

Local magnitude ( $M_L$ ) is one of the commonly used scales to estimate the size of an earthquake, and is often used to drive traffic light protocols in induced seismicity monitoring applications. For instance, Alberta Energy Regulator Subsurface Order No. 2 explicitly defines the actions to be taken as a response to induced events in terms of staged  $M_L$  thresholds. Obtaining reliable  $M_L$  estimates is critically important in terms of effectiveness of traffic light protocols due to high costs associated with red-light operation shutdowns.

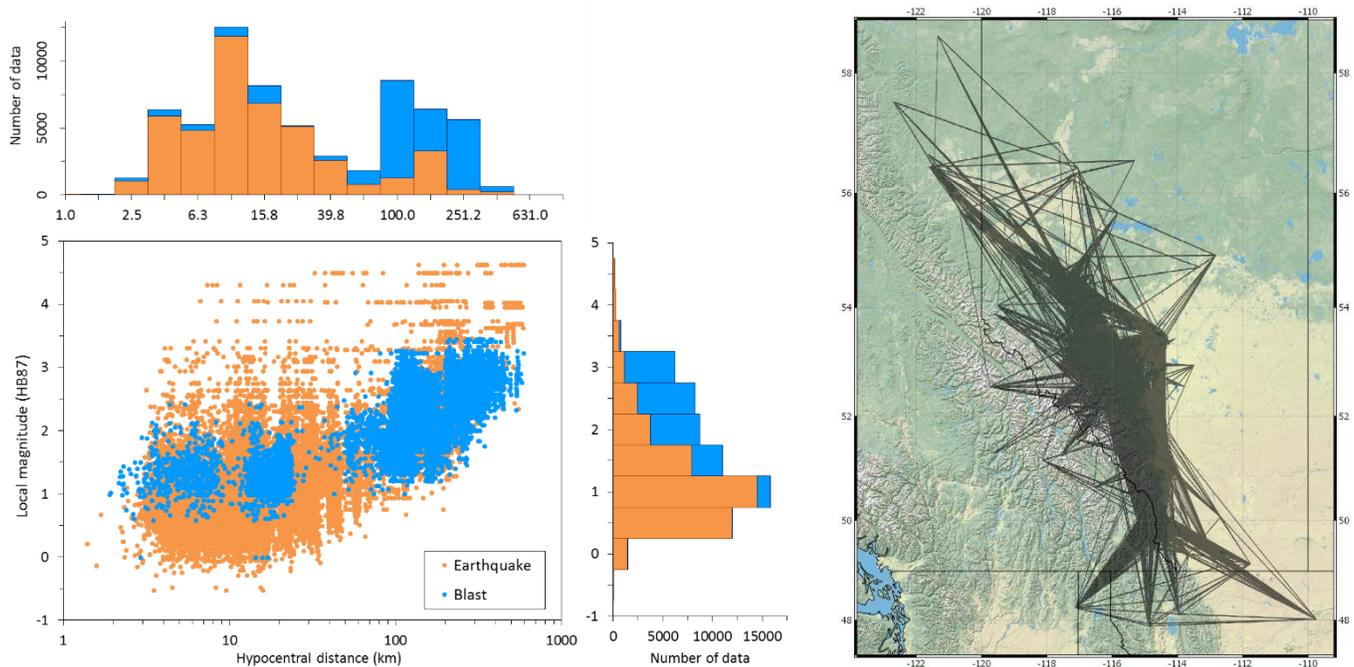
A proper correction of observed amplitudes for regional attenuation and site effects is the prerequisite for accurate magnitude estimations. Standard  $M_L$  formulas derived from California data (e.g., Hutton and Boore, 1987; Eaton, 1992) are generally used in regions where empirical data are insufficient to develop a robust regional attenuation model. This may result in biased  $M_L$  estimates if the adopted model does not comply with the attenuation characteristics of the target region.

In this study, we develop a regionally-calibrated  $M_L$  formula for western Alberta, using a rich ground-motion dataset compiled from regional and local seismic networks in Alberta. We examine the earthquakes and mining/quarry blasts in terms of their amplitude decay with distance. Both event types show similar attenuation attributes with a strong Moho bounce effect. We show that standard  $M_L$  models fail to capture the rates and shape of amplitude attenuation in western Alberta, resulting in overestimated magnitudes compared to the derived  $M_L$  formula. Our results highlight the importance of accurate region-specific modeling of attenuation attributes for induced seismicity traffic light applications.

### Amplitude Dataset

High-quality recordings of manually-reviewed seismic and blast events from September 2013 to August 2015 are compiled from regional and local networks in western Alberta. Potential blast events are identified by visual inspection of waveforms (e.g., Keephills events) and by correlation of the local origin times and event locations with the mining areas in Alberta (e.g., blasts near SW border of Alberta). Peak amplitudes of simulated Wood-Anderson (WA) instruments with static magnification of 2080 (IASPEI, 2013) are measured for analysis of regional attenuation. We consider events and stations with at least 5 amplitude readings up to

a distance of 600 km. A total of 44285 horizontal-component records from 2366 earthquakes, and 20484 horizontal-component records from 1134 mine/quarry blasts are used in this study. Figure 1 shows the magnitude and distance distribution of the amplitude dataset, and the surface projection of raypaths across the region. The compiled dataset mostly consists of earthquake records at close distances, and is dominated by blast records at far distances. Within the region of interest, the raypaths are dense and travel in every direction such that there should be no directional biases introduced.



**Figure 1.** Left – Magnitude and distance distribution of Wood-Anderson amplitudes for earthquake and blast recordings used in this study. Event magnitudes are estimated based on Hutton and Boore (1987) for preliminary assessment of the amplitude dataset. Right – Regional coverage of the surface projection of raypaths for study events.

## Model and Regression Analysis

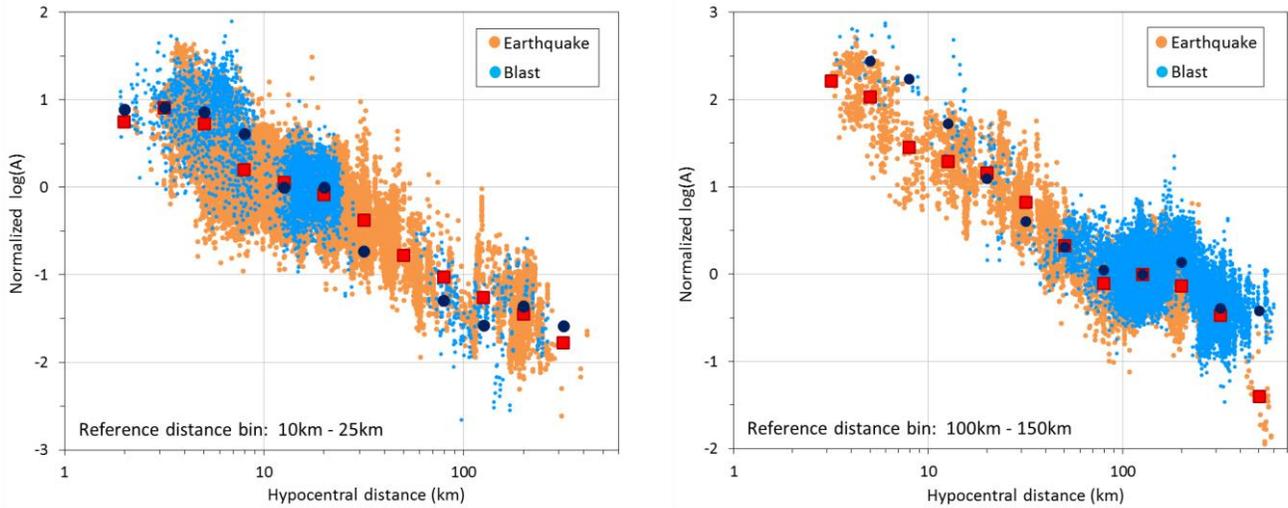
A standard formulation of Richter’s local magnitude is written as (Richter, 1935, 1958; Hutton and Boore, 1987; Eaton, 1982; Miao and Langston, 2007):

$$M_L = \log(A) - \log A_0 + S \quad (1)$$

where  $A$  is half of the peak-to-peak amplitude (mm) of a horizontal component on a standard Wood-Anderson (WA) seismometer,  $-\log A_0$  is the distance-correction function that reflects the overall attenuation attributes in the region of interest, and  $S$  is the station correction defined relative to a reference site condition. In order to maintain Richter’s (1935) original definition of  $M_L$ ,  $-\log A_0$  is defined such that 1 mm of amplitude on a WA instrument located at a reference site at 100 km away from an event would register as a magnitude 3 event.

We compare the decay of WA amplitudes with distance for earthquakes and blast events in order to gain preliminary insights on the regional attenuation attributes. For this purpose, we calculate the geometric mean of amplitudes for each event at two different reference distance bins (10 km - 25 km and 100 km - 150 km) where empirical data are abundant. We normalize the observed amplitudes event-by-event with the mean amplitude calculated for the corresponding event and reference distance bin. This exercise effectively removes the source effects from observed WA amplitudes and reveals the attenuation characteristics in the region. However, it is worth noting that the normalized amplitudes still include site effects relative to the average site condition in each reference distance bin. Both earthquakes and blast events display similar attenuation attributes, as shown in Figure 2. There is a region where attenuation of WA amplitude slows

markedly, which is believed to be due to “Moho-bounce” effect, a consequence of reflected and refracted phases joining the direct waves.



**Figure 2.** Attenuation of normalized WA amplitudes with distance for two reference distance bins: left – 10 km to 25 km, and right – 100 km to 150 km. Large symbols show the mean of normalized amplitudes calculated at log-spaced distance ranges.

Based on observations in Figure 2, we combine the amplitude datasets from seismic and blast events (despite a slight tendency for blasts to decay somewhat more steeply at close distance), and model the regional attenuation using a single trilinear function. We define the regional distance correction for western Alberta as:

$$-\log A_0 = GS' + \gamma(R - 100) + 3 \quad (2)$$

where  $\gamma$  is the coefficient of anelastic attenuation, and  $R$  is the hypocentral distance (km). The  $GS'$  term represents the geometrical spreading normalized at  $R = 100$  km to maintain the original definition of Richter (1935):

$$GS' = GS(R) - GS(R = 100\text{km}) \quad (3)$$

The decay of WA amplitudes due to geometrical spreading in western Alberta is defined as a trilinear function of hypocentral distance:

$$GS(R) = \begin{cases} b_1 \log(R) & R \leq R_1 \\ b_1 \log(R_1) + b_2 \log(R/R_1) & R_1 < R \leq R_2 \\ b_1 \log(R_1) + b_2 \log(R_2/R_1) + b_3 \log(R/R_2) & R > R_2 \end{cases} \quad (4)$$

where  $b_1$ ,  $b_2$  and  $b_3$  are rates of geometrical spreading at three distance ranges defined by transition distances  $R_1$  and  $R_2$ .

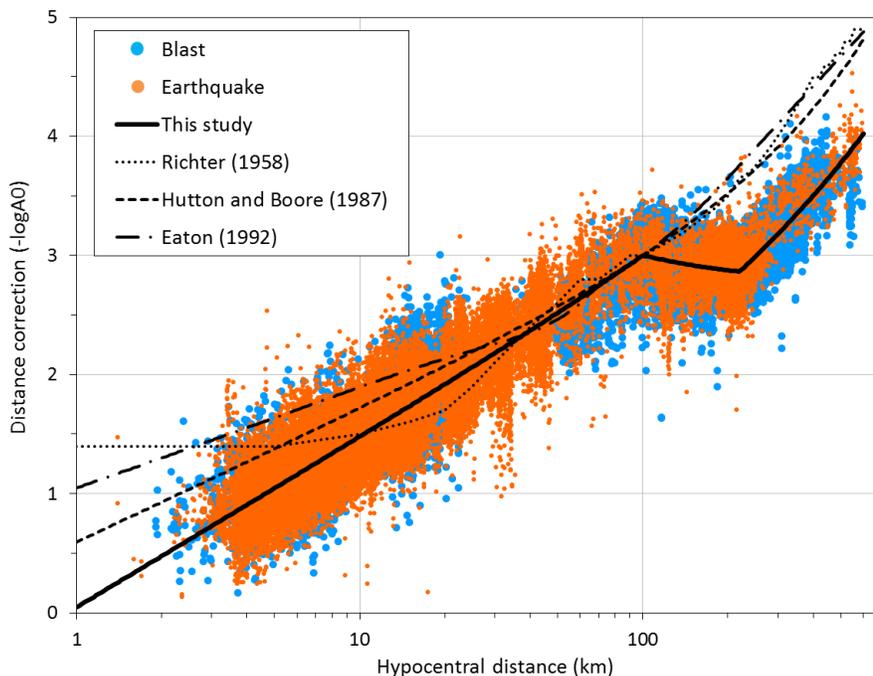
## Results

We regress observed WA amplitudes based on Equations 1-4, in order to determine the model coefficients:  $b_1$ ,  $b_2$ ,  $b_3$ ,  $R_1$ ,  $R_2$ ,  $\gamma$  and an  $S$  term for each station. We grid search transition distances within  $50 \text{ km} \leq R_1 \leq 150 \text{ km}$  and  $100 \text{ km} \leq R_2 \leq 300 \text{ km}$  ranges with 10 km increments, and calculate all other model coefficients for each  $R_1$ - $R_2$  combination via regressions. The best-fitting parameter set is selected by minimizing the mean of absolute residuals. Table 1 lists the model coefficients of distance correction derived for western Alberta.

**Table 1.** Coefficients of distance correction ( $-\log A_0$ ) for western Alberta

$R_1$	$R_2$	$b_1$	$b_2$	$b_3$	$\gamma$
100	220	1.42	-0.78	1.70	0.0011

The regionally-calibrated distance correction model shows a good agreement with the empirical data, as shown in Figure 3. However, Hutton and Boore (1987) and Eaton (1992) models, which are commonly used for magnitude estimation in absence of a regional  $M_L$  formula, fail to capture the attenuation attributes in western Alberta. Both models over-correct for distance attenuation for  $R < 30$  km and  $R > 100$  km, and do not account for observed Moho-bounce effect. Note that  $M_L$  estimates from local and regional stations are affected by the biased distance corrections if region-specific attenuation attributes are not considered in magnitude calculations. We found that Hutton and Boore (1987) and Eaton (1992) models overestimate  $M_L$  for earthquakes in western Alberta, on average, by 0.35 and 0.47 magnitude units, respectively.



**Figure 3.** Comparison of the distance correction model ( $-\log A_0$ ) developed for western Alberta (solid line) and standard models that are commonly used for magnitude estimation in absence of a regionally-derived  $M_L$  formula. Scatter dots indicate distance correction obtained from observed amplitudes after correcting for event magnitude and site effects.

## Conclusions

We developed an empirically constrained  $M_L$  formula for earthquakes in western Alberta. The new  $M_L$  relationship employs a trilinear distance correction to capture observed attenuation effects in the region. It results in unbiased magnitude estimates with distance in western Alberta, and attains systematically lower  $M_L$  values than those computed based on default California-based local magnitude models. Our findings feature the key role of region-specific attenuation modeling in magnitude calculations for induced seismicity traffic light applications.

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